Introduction to measurements Theory:

1.1 Purpose and performance of measurement systems

We begin by defining a **process** as a system which generates **information**. Examples are a chemical reactor, a jet fighter, a gas platform, a submarine, a car, a human heart, and a weather system.

Table 1.1 lists **information variables** which are commonly generated by processes:

Thus a car generates displacement, velocity and acceleration variables, and a chemical reactor generates temperature, pressure and composition variables.

Table 1.1 Common information/measured variables.

Acceleration	Density
Velocity	Viscosity
Displacement	Composition
Force–Weight	pH
Pressure	Humidity
Torque	Temperature
Volume	Heat/Light flux
Mass	Current
Flow rate	Voltage
Level	Power

We then define the **observer** as a person who needs this information from the process. This could be the car driver, the plant operator or the nurse. The purpose of the **measurement system** is to link the observer to the process, as shown in Figure 1.1. Here the observer is presented with a number which is the current value of the information variable. We can now refer to the information variable as a **measured variable**. The input to the measurement system is the **true value** of the variable; the system output is the **measured value** of the variable.

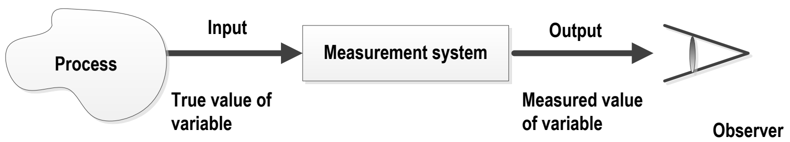

Figure 1.1 Purpose of measurement system

In an ideal measurement system, the measured value would be equal to the true value. The **accuracy** of the system can be defined as the closeness of the measured value to the true value. A perfectly accurate system is a theoretical ideal and the accuracy of a real system is quantified using **measurement system error** *E*, where

E = measured value − true value

E = system output − system input

Thus if the measured value of the flow rate of gas in a pipe is 11.0 m3/h and the true value is 11.2 m3/h, then the error *E* = −0.2 m3/h. If the measured value of the rotational speed of an engine is 3140 rpm and the true value is 3133 rpm, then *E* = +7 rpm. Error is the main performance indicator for a measurement system.

1.2 Structure of measurement systems

The measurement system consists of several elements or blocks. It is possible to identify four types of element, although in a given system one type of element may be missing or may occur more than once. The four types are shown in Figure 1.2 and can be defined as follows.

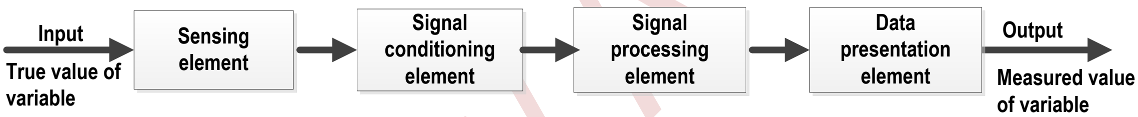

Figure 1.2 General structure of measurement system.

Sensing element

This is in contact with the process and gives an output which depends in some way on the variable to be measured. Examples are:

- Thermocouple where millivolt E.M.F. depends on temperature
- Strain gauge where resistance depends on mechanical strain
- Orifice plate where pressure drop depends on flow rate.

If there is more than one sensing element in a system, the element in contact with the process is termed the primary sensing element, the others secondary sensing elements.

Signal conditioning element

This takes the output of the sensing element and converts it into a form more suitable for further processing, usually a D.C. voltage, D.C. current or frequency signal. Examples are:

- Deflection bridge which converts an impedance change into a voltage change
- Amplifier which amplifies millivolts to volts
- Oscillator which converts an impedance change into a variable frequency voltage.

Signal processing element

This takes the output of the conditioning element and converts it into a form more suitable for presentation. Examples are:

- Analogue-to-digital converter (ADC) which converts a voltage into a digital form for input to a computer
- Computer which calculates the measured value of the variable from the incoming digital data.

Typical calculations are:

- Computation of total mass of product gas from flow rate and density data
- Integration of chromatograph peaks to give the composition of a gas stream
- Correction for sensing element non-linearity.

Data presentation element

This presents the measured value in a form which can be easily recognized by the observer. Examples are:

- Simple pointer–scale indicator
- Chart recorder
- Alphanumeric display
- Visual display unit (VDU).

1.3 Examples of measurement systems

Figure 1.3 shows some typical examples of measurement systems. Figure 1.3(a) shows a temperature system with a thermocouple sensing element; this gives a millivolt output. Signal conditioning consists of a circuit to compensate for changes in reference junction temperature, and an amplifier. The voltage signal is converted into digital form using an analogue-to-digital converter, the computer corrects for sensor non-linearity, and the measured value is displayed on a VDU.

In Figure 1.3(b) the speed of rotation of an engine is sensed by an electromagnetic tachogenerator which gives an a.c. output signal with frequency proportional to speed. The Schmitt trigger converts the sine wave into sharp-edged pulses which are then counted over a fixed time interval. The digital count is transferred to a computer which calculates frequency and speed, and the speed is presented on a digital display.

The flow system of Figure 1.3(c) has an orifice plate sensing element; this gives a differential pressure output. The differential pressure transmitter converts this into a current signal and therefore combines both sensing and signal conditioning stages. The ADC converts the current into digital form and the computer calculates the flow rate, which is obtained as a permanent record on a chart recorder. The weight system of Figure 1.3(d) has two sensing elements: the primary element is a cantilever which converts weight into strain; the strain gauge converts this into a change in electrical resistance and acts as a secondary sensor. There are two

signal conditioning elements: the deflection bridge converts the resistance change into millivolts and the amplifier converts millivolts into volts. The computer corrects for non-linearity in the cantilever and the weight is presented on a digital display.

The word '**transducer**' is commonly used in connection with measurement and instrumentation. This is a manufactured package which gives an output voltage (usually) corresponding to an input variable such as pressure or acceleration. We see therefore that such a transducer may incorporate both sensing and signal conditioning elements; for example a weight transducer would incorporate the first four elements shown in Figure 1.3(d).

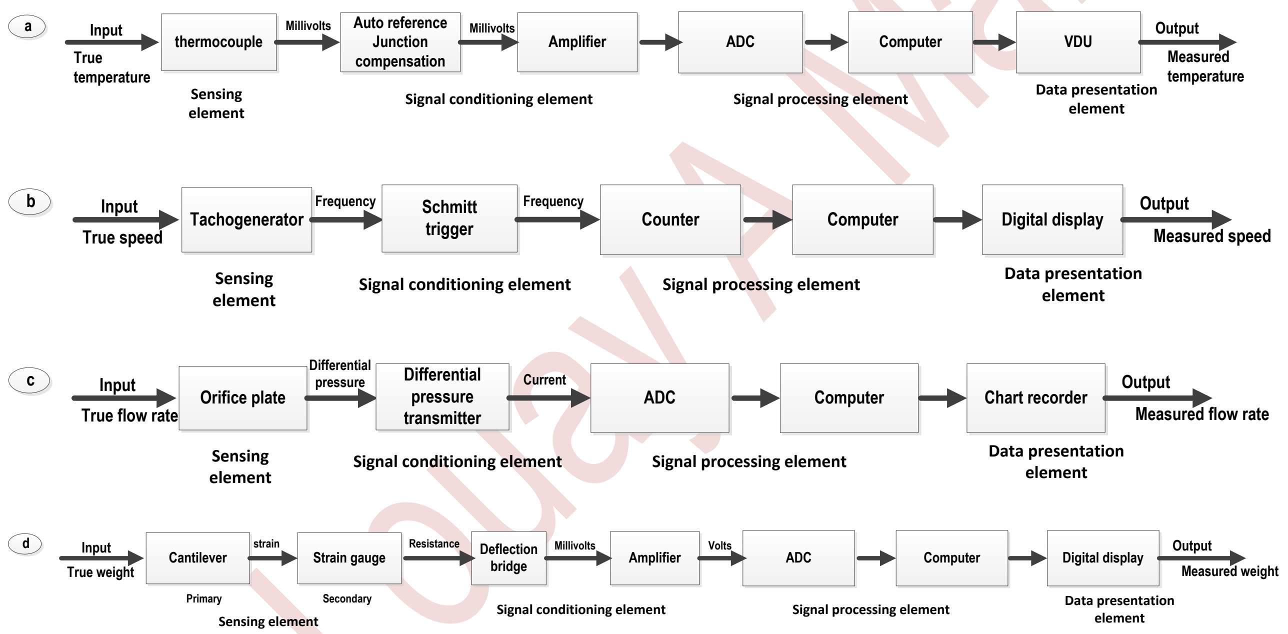

Figure 1.3 Examples of measurement systems.

Calibration:

Principles of Calibration

Calibration consists of comparing the output of the instrument or sensor under test against the output of an instrument of known accuracy when the same input (the measured quantity) is applied to both instruments. This procedure is carried out for a range of inputs covering the whole measurement range of the instrument or sensor. Calibration ensures that the measuring accuracy of all instruments and sensors used in a measurement system is known over the whole measurement range, provided that the calibrated instruments and sensors are used in environmental conditions that are the same as those under which they were calibrated. For use of instruments and sensors under different environmental conditions, appropriate correction has to be made for the ensuing modifying inputs. Whether applied to instruments or sensors, calibration procedures are identical, and hence only the term instrument will be with the understanding that whatever is said for instruments applies equally well to single measurement sensors.

Instruments used as a standard in calibration procedures are usually chosen to be of greater inherent accuracy than the process instruments that they are used to calibrate. Because such instruments are only used for calibration purposes, greater accuracy can often be achieved by specifying a type of instrument that would be unsuitable for normal process measurements. In practice, high-accuracy, null-type instruments are used very commonly for calibration duties, as the need for a human operator is not a problem in these circumstances.

Instrument calibration has to be repeated at prescribed intervals because the characteristics of any instrument change over a period. Changes in instrument characteristics are brought about by such factors as mechanical wear, and the effects of dirt, dust, fumes, chemicals, and temperature change in the operating environment. To a great extent, the magnitude of the drift in characteristics depends on the amount of use an instrument receives and hence on the amount of wear and the length of time that it is subjected to the operating environment. However, some drift also occurs even in storage as a result of aging effects in components within the instrument.

The type of instrument, its frequency of use, and the prevailing **environmental conditions** all strongly influence the calibration frequency necessary, and because so many factors are involved, it is difficult or even impossible to determine the required frequency of instrument recalibration from theoretical considerations. Instead, practical experimentation has to be applied to determine the rate of such changes. Once the maximum permissible measurement error has been defined, knowledge of the rate at which the characteristics of an instrument change allows a time interval to be calculated that represents the moment in time when an instrument will have reached the bounds of its acceptable performance level. The instrument must be recalibrated either at this time or earlier. This measurement error level that an instrument reaches just before recalibration is the error bound that must be quoted in the documented specifications for the instrument.

Control of Calibration Environment

Any instrument used as a standard in calibration procedures must be kept solely for calibration duties and must never be used for other purposes. Most particularly, it must not be regarded as a spare instrument that can be used for process measurements if the instrument normally used for that purpose breaks down. Proper provision for process instrument failures must be made by keeping a spare set of process instruments. Standard calibration instruments must be totally separate.

To ensure that these conditions are met, the calibration function must be managed and executed in a professional manner. This will normally mean setting aside a particular place within the instrumentation department of a company where all calibration operations take place and where all instruments used for calibration are kept. As far as possible this should take the form of a separate room rather than a sectioned-off area in a room used for other purposes as well. This will enable better environmental control to be applied in the calibration area and will also offer better protection against unauthorized handling or use of calibration instruments. The level of environmental control required during calibration should be considered carefully with due regard to what level of accuracy is required in the calibration procedure, but should not be over specified, as this will lead to unnecessary expense. Full air conditioning is not normally required for calibration at this level, as it is very expensive, but sensible precautions should be taken to guard the area from extremes of heat or cold; also, good standards of cleanliness should be maintained.

While it is desirable that all calibration functions are performed in this carefully controlled environment, it is not always practical to achieve this. Sometimes, it is not convenient or possible to remove instruments from a process plant, and in these cases, it is standard practice to calibrate them in situ. In these circumstances, appropriate corrections must be made for the deviation in the calibration environmental conditions away from those specified. This practice does not obviate the need to protect calibration instruments and maintain them in constant conditions in a calibration laboratory at all times other than when they are involved in such calibration duties on plant.

As far as management of calibration procedures is concerned, it is important that the performance of all calibration operations is assigned as the clear responsibility of just one person. That person should have total control over the calibration function and be able to limit access to the calibration laboratory to designated, approved personnel only. Only by giving this appointed person total control over the calibration function can the function be expected to operate efficiently and effectively. Lack of such definite management can only lead to unintentional neglect of the calibration system, resulting in the use of equipment in an out-of-date state of calibration and subsequent loss of traceability to reference standards.

Professional management is essential so that the customer can be assured that an efficient calibration system is in operation and that the accuracy of measurements is guaranteed.

Calibration procedures that relate in any way to measurements used for quality control functions are controlled by the international standard ISO 9000 (this subsumes the old British quality standard BS 5750). One of the clauses in ISO 9000 requires that all persons using calibration equipment be adequately trained. The manager in charge of the calibration function is clearly responsible for ensuring that this condition is met. Training must be adequate and targeted at the particular needs of the calibration systems involved. People must understand what they need to know and especially why they must have this information. Successful completion of training courses should be marked by the award of qualification certificates. These attest to the proficiency of personnel involved in calibration duties and are a convenient way of demonstrating that the ISO 9000 training requirement has been satisfied.

Calibration Chain and Traceability

The calibration facilities provided within the instrumentation department of a company provide the first link in the calibration chain. Instruments used for calibration at this level are known as ***working standards***. As such, working standard instruments are kept by the instrumentation department of a company solely for calibration duties, and for no other purpose, and then it can be assumed that they will maintain their accuracy over a reasonable period of time because use-related deterioration in accuracy is largely eliminated. However, over the longer term, the characteristics of even such standard instruments will drift, mainly due to aging effects in components within them. Therefore, over this longer term, a program must be instituted for calibrating working standard instruments at appropriate intervals of time against instruments of yet higher accuracy. The instrument used for calibrating working standard instruments is known as a ***secondary reference standard***. This must obviously be a very well-engineered instrument that gives high accuracy and is stabilized against drift in its performance with time. This implies that it will be an expensive instrument to buy. It also requires that the environmental conditions in which it is used be controlled carefully in respect of ambient temperature, humidity, and so on.

When the working standard instrument has been calibrated by an **authorized standards laboratory**, a calibration certificate will be issued. This will contain at least the following information:

- identification of the equipment calibrated
- calibration results obtained
- measurement uncertainty
- any use limitations on the equipment calibrated
- date of calibration
- authority under which the certificate is issued

The establishment of a company standards laboratory to provide a calibration facility of the required quality is economically viable only in the case of very large companies where large numbers of instruments need to be

calibrated across several factories. In the case of small to medium size companies, the cost of buying and maintaining such equipment is not justified.

Instead, they would normally use the calibration service provided by various companies that specialize in offering a standards laboratory. What these specialist calibration companies do effectively is to share out the high cost of providing this highly accurate but infrequently used calibration service over a large number of companies. Such standards laboratories are closely monitored by national standards organizations.

National standards organizations usually monitor both instrument calibration and mechanical testing laboratories. The national standards organizations lay down strict conditions that a standards laboratory has to meet before it is approved. These conditions control laboratory management, environment, equipment, and documentation. The person appointed as head of the laboratory must be suitably qualified, and independence of operation of the laboratory must be guaranteed. The management structure must be such that any pressure to rush or skip calibration procedures for production reasons can be resisted. As far as the laboratory environment is concerned, proper temperature and humidity control must be provided, and high standards of cleanliness and housekeeping must be maintained. All equipment used for calibration purposes must be maintained to reference standards and supported by calibration certificates that establish this traceability. Finally, full documentation must be maintained. This should describe all calibration procedures, maintain an index system for recalibration of equipment, and include a full inventory of apparatus and traceability schedules. Having met these conditions, a standards laboratory becomes an accredited laboratory for providing calibration services and issuing calibration certificates. This accreditation is reviewed at approximately 12 monthly intervals to ensure that the laboratory is continuing to satisfy the conditions for approval laid down.

Primary reference standards, describe the highest level of accuracy achievable in the measurement of any particular physical quantity. All items of equipment used in standards laboratories as secondary reference standards have to be calibrated themselves against primary reference standards at appropriate intervals of time. This procedure is acknowledged by the issue of a calibration certificate in the standard way.

National standards organizations maintain suitable facilities for this calibration. In the United States, this is the National Bureau of Standards, and in the United Kingdom it is the National Physical Laboratory. Similar national standards organizations exist in many other countries. In certain cases, such primary reference standards can be located outside national standards organizations. For instance, the primary reference standard for dimension measurement is defined by the wavelength of the orange-red line of krypton light, and it can therefore be realized in any laboratory equipped with an interferometer. In certain cases (e.g., the measurement of viscosity), such primary reference standards are not available and reference standards for calibration are achieved by collaboration between several national standards organizations who perform

measurements on identical samples under controlled conditions [ISO 5725 (1994) and ISO 5725-2/Cor1 (2002)].

What has emerged from the foregoing discussion is that calibration has a chain-like structure in which every instrument in the chain is calibrated against a more accurate instrument immediately above it in the chain, as shown in Figure 1.4. All of the elements in the calibration chain must be known so that the calibration of process instruments at the bottom of the chain is traceable to the fundamental measurement standards. This knowledge of the full chain of instruments involved in the calibration procedure is known as traceability and is specified as a mandatory requirement in satisfying the ISO 9000 standard. Documentation must exist that shows that process instruments are calibrated by standard instruments linked by a chain of increasing accuracy back to national reference standards. There must be clear evidence to show that there is no break in this chain.

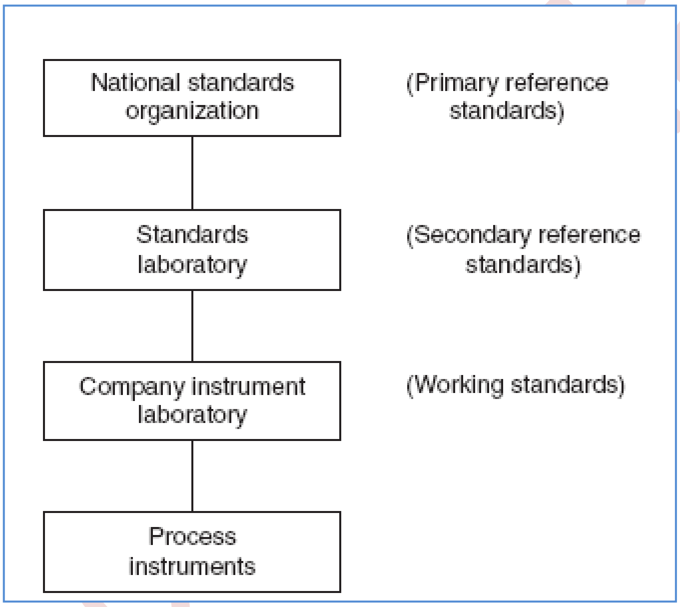

Figure 1.4 Instrument calibration chain

Example of micrometers typical calibration chain:

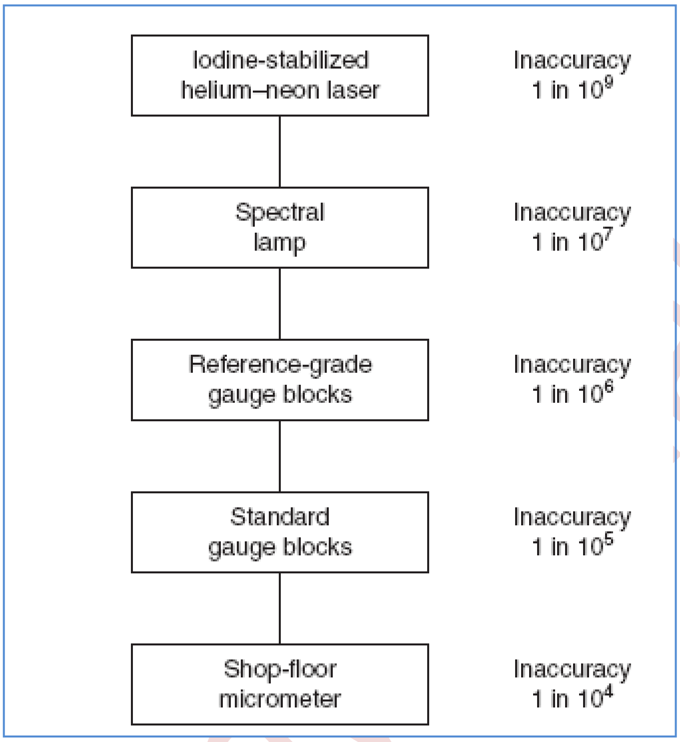

Figure 1.5 Typical calibration chain for micrometers.

To illustrate a typical calibration chain, consider the calibration of micrometers (Figure 1.5). A typical shop floor micrometer has an uncertainty (inaccuracy) of less than 1 in 10^4. These would normally be calibrated in the instrumentation department or standards laboratory of a company against laboratory standard gauge blocks with a typical uncertainty of less than 1 in 10^5. A specialist calibration service company would provide facilities for calibrating these laboratory standard gauge blocks against reference-grade gauge blocks with a typical uncertainty of less than 1 in 10^6. More accurate calibration equipment still is provided by national standards organizations. The National Bureau of Standards and National Physical Laboratory maintain two sets of standards for this type of calibration, a working standard and a primary standard. Spectral lamps are used to provide a working reference standard with an uncertainty of less than 1 in 10^7. The primary standard is provided by an iodine-stabilized helium–neon laser that has a specified uncertainty of less than 1 in 10^9. All of the links in this calibration chain must be shown in any documentation that describes the use of micrometers in making quality-related measurements.

Calibration Records

An essential element in the maintenance of measurement systems and the operation of calibration procedures is the provision of full documentation. This must give a full description of the measurement requirements throughout the workplace, instruments used, and calibration system and procedures operated. Individual calibration records for each instrument must be included within this.

This documentation is a necessary part of the quality manual, although it may exist physically as a separate volume if this is more convenient. An overriding constraint on the style in which the documentation is presented is that it should be simple and easy to read. This is often facilitated greatly by a copious use of appendices.

The starting point in the documentation must be a statement of what measurement limits have been defined for each measurement system documented. Such limits are established by balancing the costs of improved accuracy against customer requirements, and also with regard to what overall quality level has been specified in the quality manual. The technical procedures required for this, which involve assessing the type and magnitude of relevant measurement errors.

Instruments specified for each measurement situation must be listed next. This list must be accompanied by full instructions about the proper use of the instruments concerned. These instructions will include details about any environmental control or other special precautions that must be taken to ensure that the instruments provide measurements of sufficient accuracy to meet the measurement limits defined. The proper training courses appropriate to plant personnel who will use the instruments must be specified.

Having disposed of the question about what instruments are used, documentation must go on to cover the subject of calibration. Full calibration is not applied to every measuring instrument used in a workplace because ISO 9000 acknowledges that formal calibration procedures are not necessary for some equipment where it is uneconomic or technically unnecessary because the accuracy of the measurement involved has an insignificant effect on the overall quality target for a product. However, any equipment excluded from calibration procedures in this manner must be specified as such in the documentation. Identification of equipment that is in this category is a matter of informed judgment.

For instruments that are the subject of formal calibration, documentation must specify what standard instruments are to be used for the purpose and define a formal procedure of calibration. This procedure must include instructions for the storage and handling of standard calibration instruments and specify the required environmental conditions under which calibration is to be performed. Where a calibration procedure for a particular instrument uses published standard practices, it is sufficient to include reference to that standard procedure in the documentation rather than to reproduce the whole procedure. Whatever calibration system is established, a formal review procedure must be defined in the documentation that ensures its continued effectiveness at regular intervals. The results of each review must also be documented in a formal way.

A standard format for the recording of calibration results should be defined in the documentation. A separate record must be kept for every instrument present in the workplace, irrespective of whether the instrument is normally in use or is just kept as a spare. A form similar to that shown in Figure 4.3 should be used that includes details of the instrument's description, required calibration frequency, date of each calibration, and calibration results on each occasion. Where appropriate, documentation must also define the manner in which calibration results are to be recorded on the instruments themselves.

Documentation must specify procedures that are to be followed if an instrument is found to be outside the calibration limits. This may involve adjustment, redrawing its scale, or withdrawing an instrument, depending on the nature of the discrepancy and the type of instrument involved. Instruments withdrawn will either be repaired or be scrapped. In the case of withdrawn instruments, a formal procedure for marking them as such must be defined to prevent them being put back into use accidentally.

Two other items must also be covered by the calibration document. A)The traceability of the calibration system back to national reference standards must be defined and supported by calibration certificates (figure 1.6). B)Training procedures must also be documented, specifying the particular training courses to be attended by various personnel and what, if any, refresher courses are required.

Type of instrument:	Company serial number:	
Manufacturer's part number:	Manufacturer's serial number:	
Measurement limit:	Date introduced:	
Location:		
Instructions for use:		
Calibration frequency:	Signature of person responsible for calibration:	
CALIBRATION RECORD		
Calibration date	Calibration results	Calibrated by

Figure 1.6 Example of temperature calibration simple.

Definitions and classification of variables:

Measurement Units

The first measurement units were those used in barter trade to quantify the amounts being exchanged and to establish clear rules about the relative values of different commodities. Such early systems of measurement were based on whatever was available as a measuring unit. For purposes of measuring length, the human torso was a convenient tool and gave us units of the hand, the foot, and the cubit. Although generally adequate for barter trade systems, such measurement units are, of course, imprecise, varying as they do from one person to the next. Therefore, there has been a progressive movement toward measurement units that are defined much more accurately.

The first improved measurement unit was a unit of length (the meter) defined as 10^{-7} times the polar quadrant of the earth. A platinum bar made to this length was established as a standard of length in the early part of the 19th century. This was superseded by a superior quality standard bar in 1889, manufactured from a platinum–iridium alloy. Since that time, technological research has enabled further improvements to be made in the standard used for defining length. First, in 1960, a standard meter was redefined in terms of 1.65076373×10^6 wavelengths of the radiation from krypton-86 in vacuum. More recently, in 1983, the meter was redefined yet again as the length of path traveled by light in an interval of 1/299,792,458 seconds. In a similar fashion, standard units for the measurement of other physical quantities have been defined and progressively improved over the years. The latest standards for defining the units used for measuring a range of physical variables are given in Table 1.1.

The early establishment of standards for the measurement of physical quantities proceeded in several countries at broadly parallel times; in consequence, several sets of units emerged for measuring the same physical variable. For instance, length can be measured in yards, meters, or several other units. Apart from the major units of length, subdivisions of standard units exist such as feet, inches, centimeters, and millimeters, with a fixed relationship between each fundamental unit and its subdivisions. Yards, feet, and inches belong to the Imperial system of units, which is characterized by having varying and cumbersome multiplication factors relating fundamental units to subdivisions such

as 1760 (miles to yards), 3 (yards to feet), and 12 (feet to inches). The metric system is an alternative set of units, which includes, for instance, the unit of the meter and its centimeter and millimeter subdivisions for measuring length. All multiples and subdivisions of basic metric units are related to the base by factors of 10 and such units are therefore much easier to use than Imperial units. However, in the case of derived units such as velocity, the number of alternative ways in which these can be expressed in the metric system can lead to confusion.

Table 1.1 Definitions of Standard Units

(a) Fundamental Units		
Physical Quantity	**Standard**	**Definition**
Length	Meter/ symbol	Length of path traveled by light in an interval of 1/299,792,458 seconds
Mass	Kilogram kg	Mass of a platinum–iridium cylinder kept in the International Bureau of Weights and Measures, Sevres, Paris
Time	Second s	9.192631770 x10^9 cycles of radiation from vaporized cesium 133 (an accuracy of 1 in 10^{12} or one second in 36,000 years)
Temperature	Degrees K	Temperature difference between absolute zero Kelvin and the triple point of water is defined as 273.16 K
Current	Amphere A	One ampere is the current flowing through two infinitely long parallel conductors of negligible cross section placed 1 meter apart in vacuum and producing a force of 2 x 10^{-7} newtons per meter length of conductor
Luminous intensity	Candela cd	source emitting monochromatic radiation at a frequency of 540 terahertz (Hz x 10^{12}) and with a radiant density in that direction of 1.4641 mW/steradian (1 steradian is the solid angle, which, having its vertex at the center of a sphere, cuts off an area of the sphere surface equal to that of a square with sides of length equal to the sphere radius)
Matter	Mole mol	Number of atoms in a 0.012-kg mass of carbon 12
(b) Supplementary Fundamental Units		
Plane angle	Radian rad	
Solid angle	Steradian sr	

As a result of this, an internationally agreed set of standard units (SI units or Syste`mes internationales d'unite´s) has been defined, and strong efforts are being made to encourage the adoption of this system throughout the world. In support of this effort, the SI system of units is used exclusively in this book. However, it should be noted that the Imperial system is still widely used in the engineering industry, particularly in the United States. The full range of fundamental SI measuring units and the further set of units derived from them are given in Tables 1.1 and 1.2.

Table 1.2 Derived SI Units

Quantity	Standard Unit	Symbol	Derivation Formula
Area	Square meter	m^2	
Volume	cubic meter	m^3	
Velocity	meter per second	m/s	
Acceleration	metre per second squared	m/s^2	
Angular velocity	radian per second	rad/s	
Angular acceleration	radian per second squared	rad/s^2	
Density	kilogram per cubic meter	kg/m^3	
Specific volume	cubic meter per kilogram	m^3/kg	
Mass flow	rate kilogram per second	kg/s	
Volume flow rate	cubic meter per second	m^3/s	
Force	newton	N	$kg\text{-}m/s^2$
Pressure	pascal	Pa	N/m^2
Torque	newton meter	N-m	
Momentum	kilogram meter per second	kg-m/s	
Moment of inertia	kilogram meter squared	$kg\text{-}m^2$	
Kinematic viscosity	square meter per second	m^2/s	
Dynamic viscosity	newton second per square meter	$N\text{-}s/m^2$	
Work, energy, heat	joule	J	N-m
Specific energy	joule per cubic meter	J/m^3	
Power	watt	W	J/s
Thermal conductivity	watt per meter Kelvin	W/m-K	
Electric charge	coulomb	C	A-s
Voltage, e.m.f., pot diff	volt	V	W/A
Electric field strength	volt per meter	V/m	
Electric resistance	ohm	Ω	V/A
Electric capacitance	farad	F	A-s/V
Electric inductance	henry	H	V-s/A
Electric conductance	siemen	S	A/V
Resistivity	Ohm-meter	Ω-m	
Permittivity	farad per meter	F/m	
Permeability	henry per meter	H/m	
Current density	ampere per square meter	A/m^2	
Magnetic flux	weber	Wb	V-s
Magnetic flux	density tesla	T	Wb/m^2
Magnetic field strength	ampere per meter	A/m	
Frequency	hertz	Hz	s^{-1}
Luminous flux	lumen	lm	cd-sr
Luminance	candela per square meter	cd/m^2	
Illumination	lux	lx	lm/m^2
Molar volume	cubic meter per mole	m^3/mol	
Molarity	mole per kilogram	mol/kg	
Molar energy	joule per mole	J/mol	