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Development of industrial metrology laboratories – A training guide

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Preface

Metrology, the science of measurement plays a vital role in modern life, though the link between metrology and human existence is not easily understood by many. Metrology plays a vital role in industry, commerce, medicine, agriculture and many other areas.

In manufacturing industry, the quality of goods produced is dependant upon the accuracy and traceability of test and measuring instruments used in the manufacturing process at various stages. In high technology sectors, the list of applications requiring accurate and precise measurement is endless.

Measurements are vital for conducting trade and commerce. From a simple transaction of a consumer purchasing an item from a shop to international transactions between buyers and sellers in different countries, the weights and measures used must practically be the same.

The practice of medicine requires, careful and sometimes difficult measurements both in diagnosis and therapy. In these the reliability of the measurements is of the utmost importance. In agriculture, testing of food products, fertilizer and pesticides is increasingly important in providing the basis for complying with regulatory requirements. The protection of the environment is another important area where accurate and reliable measurements are needed.

Service organizations heavily depend on accurate measurements to provide a quality service. For example present day telecommunication services utilise narrow bands of electro magnetic frequency to transmit messages from one location to another. Frequently, these locations are in two distinct countries of the world. Yet the circuits that carry these signals should be able to transmit them without failure. Thus accurate frequency and time measurements become vital to the provision of fault free telecommunication services.

An elaborate system of international and national laboratories are maintained throughout the world to provide accurate and traceable measurement systems,. These laboratories carry out long term basic research on measurement with the aim of advancing the frontiers of measurement science and thereby contribute to the functioning of a co-coordinated and uniform measurement system. The pinnacle of these laboratories is the International Bureau of Weights and Measures (BIPM) located in Sevres, Paris that maintains a majority of the primary standards of the international measurement system. At the national level, a primary laboratory and a number of secondary laboratories that provide measurement services to the community are operated in most countries .The secondary laboratories can be classified into two groups ;those providing industrial calibration and measurement services and laboratories carrying out legal metrology functions.

Although a number of publications have been written by many eminent metrologists describing specific measurement fields such as mass, temperature and pressure, manuals covering a number of important measurement fields are few. This manual intends to fill this gap and is primarily aimed for training of metrologists of secondary laboratories.

The manual is an introduction to fundamental measurement principles and practical techniques used in the calibration of test and measuring equipment belonging to seven measurement fields namely length, angle, mass, temperature, pressure, force and electrical metrology. SI units of measurement, fundamental concepts and uncertainty analysis are also included.

The author wishes to acknowledge gratefully many persons who assisted him during the course of preparation of this manual. The writing of this manual was undertaken as result of encouragement given by the United Nations Industrial Development Organisation (UNIDO) in particular Dr. Lalith Goonatilake, Senior Industrial Development Officer and Project Leader of the UNIDO-Sri Lanka Integrated Development Support Programme.

Dr.G.M.S de Silva

1 Units of measurement

1.1 Introduction

This chapter gives details of the International System of Units (SI) and details of other units a metrologist may come across. The definitions of SI units are those approved by the GGPM and published by the International Bureau of Weights and Measures (BIPM).

1.2 The International System of Units (SI)

1.2.1 Historical background

The creation of the decimal Metric System at the time of the French Revolution and the subsequent deposition of two platinum standards representing the metre and the kilogram , on 22 June 1799, in the Archives de la République in Paris can be seen as the first step in the development of the present International System of Units.

In 1832, Gauss strongly promoted the application of this Metric System, together with the second defined in astronomy, as a coherent system of units for the physical sciences. Gauss was the first to make absolute measurements of the Earth's magnetic field in terms of a decimal system based on the three mechanical units millimetre, gram and second for the quantities length, mass and time respectively. In later years Gauss and Weber extended these measurements to include electrical phenomena.

These applications in the field of electricity and magnetism were further developed in the 1860s under the active leadership of Maxwell and Thomson through the British Association for the Advancement of Science (BAAS). They formulated the requirement for a coherent system of units with base units and derived units. In 1874 the BAAS introduced the CGS system, a three dimensional coherent unit system based on the three mechanical units centimetre, gram and second, using prefixes ranging from micro to mega to express decimal submultiples and multiples. Subsequent development of physics as an experimental science was largely based on this system.

The sizes of the coherent CGS units in the fields of electricity and magnetism proved to be inconvenient so, in the 1880s, the BAAS and the International Electrical Congress, predecessor of the International Electrotechnical Commission (IEC), approved a mutually coherent set of practical units. Among them were the ohm for electrical resistance, the volt for electromotive force, and the ampere for electric current . After the establishment of the Convention of the Metre on 20 May 1875 the CIPM concentrated on the construction of new prototypes taking the metre and kilogram as the base units of length and mass. In 1889 the 1st CGPM sanctioned the international prototypes for the metre and the kilogram. Together with the astronomical second as unit of time, these units constituted a three-dimensional mechanical unit system similar to the CGS system, but with the base units metre, kilogram and second, the MKS system.

In 1901 Giorgi Giovanni showed that it is possible to combine the mechanical units of this metre-kilogram-second system with the practical electrical units to form a single coherent four-dimensional system by adding to the three base units a fourth unit of an electrical nature, such as the ampere or the ohm, and rewriting the equations occurring in electro magnetism in the so-called rationalized form. Giorgi's proposal opened the path to a number of new developments.

The Giorgi proposal was thoroughly discussed by the IEC, the IUPAP and other international organizations. This led the CIPM to adopt a four-dimensional system based on the metre, kilogram, second and ampere, the MKSA system, in 1946.

After an international inquiry by the BIPM, the 10th CGPM, in 1954, approved the introduction of the ampere, the kelvin and the candela as base units, respectively, for electric current, thermodynamic temperature and luminous intensity. The name Système

International d'Unités (SI) was given to the system by the 11th CGPM in 1960. At the 14th CGPM in 1971 the mole was added as a base unit for amount of substance, bringing the total number of base units to seven, completing the current version of the SI.

1.2.2 Base units

The International system of units consists of base units and derived units. The base units are given in Table 1.1.

Table 1.1 SI base units

Quantity	Unit	Symbol
length	meter	m
Mass	kilogram	kg
Time	second	s
Temperature	kelvin	K
Electric current	ampere	A
Luminous intensity	candela	cd
Amount of substance	mole	mol

The current definitions of the base units are given below :

a) Metre

The metre is defined as,

> *the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.*

This definition was adopted by the Conference Generale de Poids et Mesures (CGPM) in 1983 and fixes the velocity of light at 299 792 458 m/s.

b) Kilogram

The kilogram is defined as,

> *the mass of the international prototype kilogram maintained at the BIPM. The kilogram is the only SI base unit defined in terms of an artefact standard.*

c) Second

The second is defined,

> *' as the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.'*

d) Kelvin

The kelvin is defined,

> *'as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water'.*

e) Ampere

The ampere is defined as ,

> *'that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed one meter apart in vacuum, would produce between them a force equal to 2×10^{-7} newton per meter of length '*

f) Candela

The candela is defined as,

> *'the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.*

g) Mole

The mole is defined as,

> *'the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilograms of carbon 12.*
>
> *Note : When the mole is used ,the elementary entities must be specified and may be atoms, molecules ,ions, electrons ,other particles, or specified groups of such particles'.*

1.2.3 Derived units

SI derived units are obtained by inserting unit values of relevant base units in a physical equation. For example the SI derived unit for velocity is obtained by applying unit values in the physical equation:

$$\text{Velocity} = \frac{\text{distance}}{\text{time}}$$

$$\text{Derived unit for velocity} = \frac{1\,\text{meter}}{1\,\text{second}} = 1\,\text{m/s}$$

A list of derived units is given in Table 1.2

Table 1.2 Examples of SI derived units expressed in terms of base units

Quantity	SI unit name	Symbol
area	square meter	m^2
volume	cubic meter	m^3
speed, velocity	meter per second	m/s
acceleration	meter per second squared	m/s^2
concentration	mole per cubic meter	mol/m^3
frequency	hertz	s^{-1}
luminance	candela per square meter	cd/m^2

1.2.4 Derived units with special names

Some derived units have been given special names and symbols. These units are given in Table 1.3.In addition some derived units are formed from derived units with special names. A collection of these units is given in Table 1.4 .

A single SI unit may correspond to several different quantities. In the above table, which is not exhaustive, there are several examples. Thus the joule per kelvin (J/K) is the SI unit for the quantity heat capacity as well as for the quantity entropy; also the ampere (A) is the SI unit for the base quantity electric current as well as for the derived quantity magnetomotive force. It is therefore important not to use the unit alone to specify the quantity. This rule applies not only to scientific and technical texts but also, for example, to measuring instruments (i.e. an instrument should indicate both the unit and the quantity measured) . A derived unit can often be expressed in different ways by combining the names of base units with special names for derived units. This, however, is an algebraic freedom to be governed by common-sense physical considerations. Joule, for example, may formally be written newton metre, or even kilogram metre squared per second squared, but in a given situation some forms may be more helpful than others.

In practice, with certain quantities preference is given to the use of certain special unit names, or combinations of unit names, in order to facilitate the distinction between different quantities having the same dimension. For example, the SI unit of frequency is designated the hertz, rather than the reciprocal second, and the SI unit of angular velocity is designated the radian per second rather than the reciprocal second (in this case retaining the word radian emphasizes that angular velocity is equal to 2pi times the rotational frequency). Similarly the SI unit of moment of force is designated the newton metre rather than the joule. In the field of ionizing radiation , the SI unit of activity is designated the becquerel rather than the reciprocal second, and the SI units of absorbed dose and dose equivalent the gray and sievert , respectively, rather than the joule per kilogram .

1.2.5 Units for dimensionless quantities, quantities of dimension one

Certain quantities are defined as the ratios of two quantities of the same kind, and thus have a dimension, which may be expressed by the number one. The unit of such quantities is necessarily a derived unit coherent with the other units of the SI and, since it is formed as the ratio of two identical SI units, the unit also may be expressed by the number one. Thus the SI unit of all quantities having the dimensional product one is the number one. Examples of such quantities are refractive index, relative permeability, and friction factor. Other quantities having the unit 1 include " characteristic numbers " like the Prandtl number hcp/l a nd numbers which represent a count, such as a number of molecules, degeneracy (number of energy levels) and partition function in statistical thermodynamics. All of these quantities are described as being dimensionless, or of dimension one, and have the coherent SI unit 1. Their values are simply expressed as numbers and, in general, the unit 1 is not explicitly shown. In a few cases, however, a special name is given to this unit, mainly to avoid confusion between some compound derived units. This is the case for the radian, steradian and neper.

Table 1.3-SI derived units with special names and symbols

Derived quantity	SI derived unit			
	Name	Symbol	in terms of other SI units.	Expression in terms of SI base units
plane angle	radian [a]	rad		$m \cdot m^{-1} = 1$ [b]
solid angle	steradian [a]	sr [c]		$m^2 \cdot m^{-2} = 1$ [b]
frequency	hertz	Hz		s^{-1}
force	newton	N		$m \cdot kg \cdot s^{-2}$
pressure, stress	pascal	Pa	N / m^2	$m^{-1} \cdot kg \cdot s^{-2}$
energy, work, quantity of heat	joule	J	$N \cdot m$	$m^2 \cdot kg \cdot s^{-2}$
power, radiant flux	watt	W	J / s	$m^2 \cdot kg \cdot s^{-3}$
electric charge, quantity of electricity	coulomb	C		$s \cdot A$
electric potential difference, electromotive force	volt	V	W / A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
capacitance	farad	F	C /V	$m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$
electric resistance	ohm	Ω	V / A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$
electric conductance	siemens	S	A / V	$m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2$
magnetic flux	weber	Wb	$V \cdot s$	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
magnetic flux density	tesla	T	Wb / m^2	$kg \cdot s^{-2} \cdot A^{-1}$
inductance	henry	H	Wb / A	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
Celsius temperature	degree Celsius [d]	°C		K
luminous flux	lumen,	lm	$Cd \cdot sr$ [c]	$m^2 \cdot m^{-2} \cdot cd = cd$
illuminance	lux	lx	lm / m^2	$m^2 \cdot m^{-4} \cdot cd = m^{-2} \cdot cd$
activity (referred to a radionuclide)	becquerel	Bq		s^{-1}
absorbed dose, specific energy (imparted), kerma	gray	Gy	J / kg	$m^2 \cdot s^{-2}$
dose equivalent, ambient dose equivalent, directional dose equivalent, personal dose equivalent, organ equivalent dose	sievert	Sv	J / kg	$m^2 \cdot s^{-2}$

Notes:

a) The radian and steradian may be used with advantage in expressions for derived units to distinguish between quantities of different nature but the same dimension.

b) In practice, the symbols rad and sr are used where appropriate, but the derived unit "1" is generally omitted.

c) In photometry, the name steradian and the symbol sr are usually retained in expressions for units.

d) This unit may be used in combination with SI prefixes, e.g. millidegree Celsius, m°C.

The special names becquerel, gray and sievert were specifically introduced because of the dangers to human health which might arise from mistakes involving the units reciprocal second and the joule per kilogram.

Table 1.4 Examples of SI derived units whose names and symbols include SI derived units with special names and symbols

Quantity	SI derived unit		
	Name	Symbol	Expressed in terms of SI base unit
dynamic viscosity	pascal second	Pa · s	$m^{-1} \cdot kg \cdot s^{-1}$
moment of force	newton metre	N · m	$m^2 \cdot kg \cdot s^{-2}$
s u r face tension	newton per metre	N / m	$kg \cdot s^{-2}$
angular velocity	radian per second	rad/s	$m \cdot m^{-1} \cdot s^{-1} = s^{-1}$
angular acceleration	radian per second squared	rad/s^2	$m \cdot m^{-1} \cdot s^{-2} = s^{-2}$
h e at flux density, irradiance	watt per square metre	W/m^2	$kg \cdot s^{-3}$
h e at cap a c i t y, entropy	joule per kelvin	J / K	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1}$
specific heat capacity, specific entropy	joule per kilogram kelvin	J/(kg · K)	$m^2 \cdot s^{-2} \cdot K^{-1}$
specific energy	joule per kilogra m	J / k g	$m^2 \cdot s^{-2}$
thermal conductivity	watt per metre kelvin	W/(m · K)	$m \cdot kg \cdot s^{-3} \cdot K^{-1}$
energy density	joule per cubic metre	J / m^3	$m^{-1} \cdot kg \cdot s^{-2}$
electric field strength	volt per metre	V / m	$m \cdot kg \cdot s^{-3} \cdot A^{-1}$
electric charge density	coulomb per cubic metre	C / m^3	$m^{-3} \cdot s \cdot A$
electric flux density	coulomb per square metre	C / m^2	$m\text{-}^2 \cdot s \cdot A$
permittivity	farad per metre	F / m	$m^{-3} \cdot kg^{-1} \cdot s^4 \cdot A^2$
permeability	henry per metre	H / m	$m \cdot kg \cdot s^{-2} \cdot A^{-2}$
molar energy	joule per mole	J / mol	$m^2 \cdot kg \cdot s^{-2} \cdot mol^{-1}$
molar entropy, molar heat capacity	joule per mole kelvin	J/(mol ·K)	$m2 \cdot k g \cdot s^{-2} \cdot K^{-1}.mol^{-1}$
exposure (x and γ ray s)	coulomb per kilogra m	C/k g	$k g^{-1} \cdot s \cdot A$
absorbed dose rat e	gray per second	Gy / s	$m^2 \cdot s^{-3}$
radiant intensity,	watt per steradian	W/sr	$m^4 \cdot m^{-2} \cdot kg \cdot s^{-3} = m2 \cdot kg.s^{-3}$
radiance	watt per square metre steradian	$W / (m^2 \cdot s r)$	$m^2 \cdot m^{-2} \cdot kg \cdot s^{-3} = kg \cdot s^{-3}$

1.2.6 Decimal multiples and sub multiples

Decimal multiples and sub multiples of SI units are formed by multiplying the unit by a factor in the range 10^{-24} to 10^{24}.The factors, prefixes and prefix symbols were defined by the CGPM in 1960,1964,1975 and 1991.Table 1.5 lists all approved prefixes and symbols.

Table 1.5 Factors, prefixes and prefix symbols

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	μ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deca	da	10^{-24}	yocto	y

1.2.7 Recommendations for writing of SI unit names and symbols

a) General principles

General principles for the writing of unit symbols and numbers were first proposed by the 9th CGPM (1948). These were subsequently adopted and elaborated by ISO/TC 12 (ISO 31, Quantities and units).

b) Unit symbols

SI unit symbols (and also many non-SI unit symbols) are written as follows:

1. Roman (upright) type is used for the unit symbols. In general, unit symbols are written in lower case, but, if the name of the unit is derived from the proper name of a person, the first letter of the symbol is a capital. When the name of a unit is spelled out, it is always written in lower case, except when the name is the first word of a sentence or is the name 'degree Celsius'.
2. Unit symbols are unaltered in the plural.
3. Unit symbols are not followed by a full stop (period), except as normal punctuation at the end of a sentence.

c) Algebra of SI unit symbols

In accord with the general principles adopted by ISO/TC 12 (ISO 31), algebraic expressions involving SI unit symbols are expressed in the following formats:

1. Half-high dots or spaces are used to express a derived unit formed from two or more other units by multiplication.

   Example: N · m or N m.

2. A solidus (oblique stroke, /), a horizontal line, or a negative exponent is used to express a derived unit formed from two other units by division.

   Example: m/s or or m · s^{-1}.

3 . The solidus is not followed by a multiplication sign or by a division sign on the same line unless ambiguity is avoided by parentheses. In complicated cases, negative exponents or parentheses are used to avoid ambiguity.

   Examples: m/s^2 or m · s^{-2} not m/s/s

   m · kg/(s^3 · A) or m · kg · s^{-3} · A^{-1} not m · kg/s^3/A or m · kg/s^3 · A.

d) Rules for using SI prefixes

In accord with the general principles adopted by the ISO (ISO 31), the following rules are observed when using the SI prefixes:

1. Prefix symbols are printed in roman (upright) type with no space between the prefix symbol and the unit symbol.

2. The grouping formed by the prefix symbol attached to the unit symbol constitutes a new inseparable symbol (of a multiple or submultiple of the unit concerned) which can be raised to a positive or negative power and combined with other unit symbols to form compound unit symbols.

Examples:

$1\ cm^3 = (10^{-2}\ m)^3 = 10^{-6}\ m^3$

$1\ \mu s^{-1} = (10^{-6}\ s)^{-1} = 10^6\ s^{-1}$

$1\ V/cm = (1\ V) / (10^{-2}\ m) = 10^2\ V / m$

$1\ cm^{-1} = (10^{-2}\ m)^{-1} = 10^2\ m^{-1}$.

3. Compound prefixes, i.e. prefixes formed by the juxtaposition of two or more SI prefixes, are not used.

   Example: 1 nm not 1 mμm.

4. A prefix is never used in isolation.

   Example: $10^6/m^3$ but not M/m3.

1.3 Non SI units

The CIPM (1969), recognizing that users would wish to employ the SI with units which are not part of it but are important and widely used, listed three categories of non-SI units:

a) units to be maintained;

b) units to be tolerated temporarily;

c) units to be avoided.

In reviewing this categorization in 1996 the CIPM agreed a new classification of non-SI units: units accepted for use with the SI, Table 1.6; units accepted for use with the SI whose values are obtained experimentally, Table 1.7; and other units currently accepted for use with the SI to satisfy the needs of special interests, Table 1.8.

Table 1.6 lists non-SI units which are accepted for use with the SI. It includes units that are in continuous everyday use, in particular the traditional units of time and of angle, together with a few other units, which have assumed increasing technical importance.

Table 1.6 Non-SI units accepted for use with the International System

Name	Symbol	Value in SI units
minute	min	1 min = 60 s
hour	h	1 h = 60 min = 3600 s
day	d	1 d = 24 h = 86 400 s
degree	°	1° = (π/180) rad
minute	′	1′= (1/60)° = (π/10 800) rad
second	″	1″= (1/60)′ = (π/648 000) rad
litre	l, L	1 l = 1 dm^3 = 10^{-3} m^3
tonne	t	1 t = 10^3 k g
neper	Np	1 Np = 1
bel	B	1 B = (1/2) ln 10 (Np)

Table 1.7-Non-SI units accepted for use with the International System, whose values in SI units are obtained experimentally.

Name	Symbol	Definition	Value in SI units
electronvolt [a]	eV	(*b*)	1 e V = 1 . 602 177 33 (49) x 10^{-19} J
unified atomic mass unit [a]	u	(*c*)	1 u = 1 . 660 540 2(10) x 10^{-27} kg
astronomical unit [a]	ua	(*d*)	1 ua = 1 . 495 987 691(30) x 10^{11} m

Notes:

a) For the electronvolt and the unified atomic mass unit, values are quoted from *CODATA Bulletin* ,1986, No. 63. The value given for the astronomical unit is quoted from the IERS Conventions (1996), D. D. McCarthy ed. *IERS Technical Note* 2 1 , Obsevatoire de Paris , July 1996.

b) The electronvolt is the kinetic energy acquired by an electron in passing through a potential difference of 1 V in vacuum.

c) The unified atomic mass unit is equal to 1/12 of the mass of an unbound atom of the nuclide ^{12}C , at rest , and in its ground state. In the field of biochemistry an atomic mass unit is also called the dalton, symbol Da.

d) The astronomical unit is a unit of length approximately equal to the mean Earth-Sun distance. Its value is such that , when used to describe the motion of bodies in the Solar System, the heliocentric gravitational constant is $(0.017\ 202\ 098\ 95)^2$ $ua^3 \times d^{-2}$.

Table 1.8 Derived CGS units with special names

Name	Symbol	Value in SI units
erg (*a*)	erg	1 erg = 10^{-7} J
dyne (*a*)	dyn	1 dyn = 10^{-5} N
poise (*a*)	P	1 P = 1 dyn · s/cm^2 = 0.1 Pa · s
stokes	St	1 St = 1 cm^2/s = 10-4 m^2/s
gauss (*b*)	G	1 G ^ 10^{-4} T
oersted (*b*)	Oe	1 Oe ^ (1000/4p) A/m
maxwell (*b*)	Mx	1 Mx ^ 10^{-8} Wb
stilb (*a*)	sb	1 sb = 1 cd/cm^2 = 10^4 cd/m^2
phot	ph	1 ph = 10^4 lx
gal (*c*)	Gal	1 Gal = 1 cm/s^2 = 10^{-2} m/s^2

Notes:

a) This unit and its symbol were included in Resolution 7 of the 9th CGPM (1948; CR, 7 0) .

b) This unit is part of the so-called " electromagnetic" three-dimensional CGS system and cannot strictly be compared with the corresponding unit of the International System, which has four dimensions when only mechanical and electric quantities are considered. For this re a s o n , this unit is linked to the SI unit using the mathematical symbol for "corresponds to" (^) .

c) The gal is a special unit employed in geodesy and geophysics to express acceleration due to gravity.

1.4 Other units

This section describes some of the other units still being used in many countries. Inch-Pound units are legal in USA and UK and few other countries. Non-SI metric units are also being used in many industrial situations.

1.4.1 Length

The most widely used non-metric units for measurement of length are the inch, foot, yard and the mile. Presently, these units are also defined in terms of SI units as given below:

1 inch (in) = 25.4 millimeter exactly,

1 foot (ft) = 0.304 8 meter,

1 yard (yd) = 0.914 4 meter,

1 mile = 1.609 34 kilometer

1.4.2 Pressure

A popular non-metric unit for measurement of pressure is the pound-force per square inch (lbf/in^2).In both metric and non metric systems, sometimes pressures are erroneously indicated in mass units e.g. '200 PSI' which should correctly be written as '200 pound-force per square inch' or '200 lbf/in^2'.

The manometric units *millimeter of mercury* and *inch of water* depend on an assumed liquid density and acceleration due to gravity. Both of these assumptions inherently limit their relationship to the pascal. The use of these units is strongly discouraged internationally. However their definitions are given below:

The conventional millimeter of mercury is defined in terms of the pressure generated by a mercury column of unit length and of assigned density 13 595. kg/m^3 at 0 °C under standard gravity of 9.806 65 m/s^2.

The conventional inch of water is defined in terms of the pressure generated by a water column of unit length and of assigned density 1 000 kg/m^3 subjected to standard gravity of 9.806 65 m/s^2.

1.4.3 Force

The kilogram-force and tonne-force are the non-SI units commonly used for measurement of force. The kilogram force is the force experienced by a mass of one kilogram due to an acceleration of 9.80665 m/s^2. The acceleration of 9.80665 m/s^2 is known as standard acceleration and was introduced in order to define force units independent of the acceleration due to gravity, yet approximately equal to gravitational units. The tonne-force is equal to one thousand kilogram force, which is the same force required to accelerate a mass of 1000 kilogram through the standard acceleration (9.80665 m/s^2).

In non-metric countries the pound-force defined as the force required to accelerate a mass of one pound through the standard acceleration or the ton-force which is 2240 pound force is used. In both SI and non metric systems, sometimes force or load values are erroneously indicated in mass units e.g. '100 tonne load' which should correctly be written as 'a load of 100 tonne-force' or 'a load of 100 tf'.

1.4.4 Temperature

The degree Fahrenheit is the most commonly used non metric unit. It is related to the degree Celsius by the following relationship.

1 Degree Fahrenheit = 5/8 degree Celsius

In addition the ice point of the Fahrenheit scale is defined to be at 32 degrees Fahrenheit. The relationship between temperature on the Celsius and Fahrenheit scales are given by the equation : $^{\circ}C = \frac{5}{8}(^{\circ}F - 32)$ (1.1)

2 Fundamental concepts of measurement

2.1 Introduction

The most important fundamental concepts of measurement except the concepts of uncertainty of measurement are explained in this chapter. The concepts of uncertainty are discussed in Chapter 9.

2.2 Fundamental concepts

2.2.1 Measurand and Influence Quantity

The specific quantity determined in a measurement process is known as the *measurand*. A complete statement of the *measurand* also requires specification of other quantities, for example temperature, pressure, humidity etc., which may affect the value of the *measurand*. These quantities are known as *influence quantities*.

For example, in an experiment performed to determine the density of a sample of water at a specific temperature (say 20^0C), the *measurand* is the 'density of water at 20^0 C'. In this instance the only *influence quantity* specified is the temperature, namely 20^0 C.

2.2.2 True value (of a quantity)

The *true value* of a quantity is defined as the value consistent with its definition. This implies that there are no measurement errors in the realisation of the definition. For example, the density of a substance is defined as mass per unit volume. If mass and volume of the substance could be determined without making measurement errors, then the true value of the density can be obtained. Unfortunately in practice both these quantities can not be determined without experimental error. Therefore the *true value* of a quantity can not be determined experimentally.

2.2.3 Nominal value and conventional true value

The *nominal value* is the approximate or rounded-off value of a material measure or characteristic of a measuring instrument. For example, when we refer to a resistor as 100 ohms or to a weight as 1 kg, we are using their nominal values. Their exact values known as *conventional true values* may be 99.98 ohms and 1.0001 kg Respectively. The *conventional true value* is obtained by comparing the test item with a higher level measurement standard under defined conditions. If we take the example of the 1 kg weight, the conventional true value is the mass value of the weight as defined in the OIML (International Organisation for Legal Metrology) international recommendation RI 33. i.e. the apparent mass value of the weight, determined using weights of density 8000 kg/m^3 in air of density 1.2 kg/m^3 at 20^0 C with a specified uncertainty figure. The conventional value of a weight is usually expressed in the form 1.001 g ± 0.001 g.

2.2.4 Error and relative error of measurement

The difference between the result of a measurement and its *true value* is known as the *error* of the measurement. Since a *true value* can not be determined, the *error* as defined can not be determined as well. A *conventional true value* is therefore used in practice to determine an *error*.

The *relative error* is obtained by dividing the *error* by the average of the measured value. When it is necessary to distinguish *error* from *relative error*, the former is sometimes called *absolute error* of measurement. As the error could be positive or negative another term absolute *value of error*, is used to express the magnitude (or modulus) of the error.

As an example suppose we want to determine the error of a digital multimeter at a nominal voltage level of 10 volts, DC. The multimeter is connected to a DC voltage standard

supplying a voltage of 10 volts DC and the reading is noted down. The procedure is repeated several times, say 5 times. The mean of the five readings is calculated, and is found to be 10.2 volts.

The error is then calculated as 10.2 –10.0 = + 0.2 Volts. The relative error is obtained by dividing 0.2 volts by 10.2 volts, giving 0.02. The relative error as a percent is obtained by multiplying the relative error (0.02) by 100 , i.e. the relative error is 2 percent of the reading.

In this example a conventional true value is used, namely the voltage of 10 volts DC supplied by the voltage standard, to determine the error of the instrument.

2.2.5 Random error

The *random error* of measurement arises from unpredictable variations of one or more influence quantities. The effects of such variations are known as *random effects*. For example, in determining the length of a length bar or gauge block, the variation of temperature of the environment gives rise to an error in the measured value. This error is due to a random effect, namely the unpredictable variation of the environmental temperature. It is not possible to compensate for random errors. However the uncertainties arising from random effects can be quantified by repeating the experiment a number of times.

2.2.6 Systematic error

An error that occurs due to a more or less constant effect is a *systematic error*. If the zero of a measuring instrument has been shifted by a constant amount this would give rise to a systematic error. In measuring the voltage across a resistance using a voltmeter the finite impedance of the voltmeter often causes a systematic error. A correction can be computed if the impedance of the voltmeter and the value of the resistance are known.

Often, measuring instruments and systems are adjusted or calibrated using measurement standards and reference materials to eliminate systematic effects. However the uncertainties associated with the standard or the reference material are incorporated in the uncertainty of the calibration.

2.2.7 Accuracy and Precision

The terms *accuracy* and *precision* are often misunderstood or confused. The accuracy of a measurement is the degree of its closeness to the *true value*. The precision of a measurement is the degree of scatter of the measurement result, when the measurement is repeated a number of times under specified conditions.

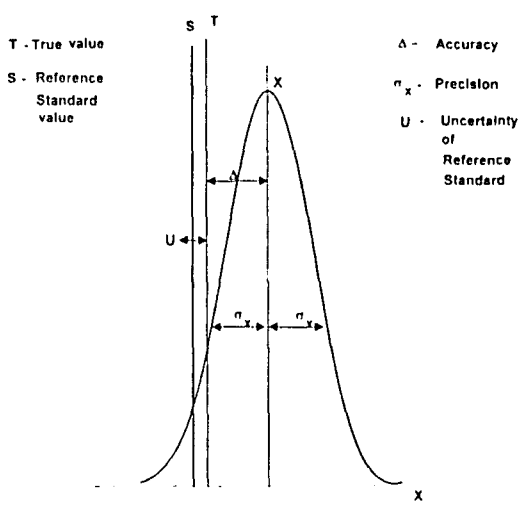


Figure 2.1 Accuracy, precision and true value

In Figure 2.1 the results obtained from a measurement experiment using a measuring instrument is plotted as a frequency distribution. The vertical axis represents the frequency of the measurement result and the horizontal axis represents the values of the results (X). The central vertical line represents the mean value of all the measurement results. The

vertical line marked **T** represents the *true value* of the measurand .The difference between the mean value and the **T** line is the *accuracy* of the measurement. The standard deviation (σ_x) of all the measurement results about the mean value is a quantitative measure for the precision of the measurement .

Unfortunately the accuracy defined in this manner can not be determined, as the true value (**T**) of a measurement can not be obtained due to errors prevalent in the measurement process. The only way to obtain an estimate of accuracy is to use a higher level measurement standard in place of the measuring instrument to perform the measurement and use the resulting mean value as the *true value*. This is what is usually done in practice. The line (**S**) represents the mean value obtained using a higher level measurement standard.

Thus accuracy figures quoted by instrument manufacturer's in their technical literature is the difference between the measurement result displayed by the instrument and the value obtained when a higher level measurement standard is used to perform the measurement. In the case of simple instruments the accuracy indicated is usually the calibration accuracy e.g. in the calibration of a micrometer a series of gauge blocks is used. If the values displayed by the micrometer over its usable range falls within ± 0.01 mm of the values assigned to the gauge blocks, then the accuracy of the micrometer is reported as ± 0.01 mm.

It can be seen that the definition of *error* given previously is very similar to the definition of *accuracy*. In fact *error* and *accuracy* are interchangeable terms. Some prefer to use the term *error* and others prefer *accuracy*. Generally instrument manufacturers prefer the term *accuracy*, as they do not wish to highlight the fact that their instruments have errors.

Relative accuracy and percent relative accuracy are also concepts in use. The definitions of these are similar to those of *relative error* and *percent relative error*. i.e *relative accuracy* is obtained by dividing *accuracy* by the average measured result and *percent relative accuracy* is computed by multiplying relative accuracy by 100.

2.2.8 Calibration

Calibration is the process of comparing the indication of an instrument or the value of a material measure (e.g value of a weight or graduations of a length measuring ruler) against values indicated by a measurement standard under specified conditions. In the process of calibration of an instrument or material measure the test item is either adjusted or correction factors are determined.

Not all instruments or material measures are adjustable. In case the instrument cannot be adjusted, it is possible to determine correction factors, although this method is not always satisfactory due to a number of reasons, the primary one being the non-linearity of response of most instruments.

For example, in the calibration of a mercury in glass thermometer between 0 °C and 100 ° C, say the calibration was carried out at six test temperatures, 0 °C , 20 °C, 40 °C, 60 °C ,80 °C, and 100 °C . Corrections are determined for each test temperature by taking the difference of readings between the test thermometer and the reference thermometer used for the calibration. These corrections can be are valid only at the temperatures of calibration. The corrections at intermediate temperatures can not be determined by interpolation. e.g the correction for 30 °C can not be determined by interpolating the corrections corresponding to 20 °C and 40 °C.

In the case of material measures for example a test weight; either determination of the conventional mass value or adjustment of the mass value (in adjustable masses only) by addition or removal of material is performed. However in the case of many other material measures such as meter rulers, gauge blocks , standard resistors adjustment is not possible. In such cases the conventional value of the item is determined.

Some instruments used for measurement of electrical parameters are adjustable, e.g. multimeters, oscilloscopes, function generators.

2.2.9 Hierarchy of measurement standards

Measurement standards are categorized into different levels, namely primary, secondary and working standards forming a *hierarchy*. Primary standards have the highest metrological quality and their values are not referenced to other standards of the same quantity. For example the International Prototype kilogram maintained at the International Bureau of Weights and Measures (BIPM) is the primary standard for mass measurement. This is the highest level standard for mass measurement and is not referenced to any further standard.

A *secondary standard* is a standard whose value is assigned by comparison with a primary standard of the same quantity. The national standard kilograms maintained by many countries are secondary standards as the value of these kilograms is determined in comparison to the primary standard kilogram maintained at the International Bureau of Weights and Measures (BIPM).

A standard, which is used routinely to calibrate or check measuring instruments or material measures, is known as a *working standard*. A working standard is periodically compared against a secondary standard of the same quantity. For example the weights used for calibration of balances and other weights are working standards.

The terms *national primary standard, secondary standard* and *tertiary standard* are used to describe the *hierarchy* of national measurement standards maintained in a given country. Here the word primary standard is used in the sense that it is the highest-level standard maintained in a given country for a particular quantity. This

standard may or may not be a primary standard in terms of the *metrological hierarchy* described in the previous paragraph. e.g. Many countries maintain an iodine stabilized helium neon laser system for realization of the national meter. This

is a case of a metrological primary standard being used as a national primary

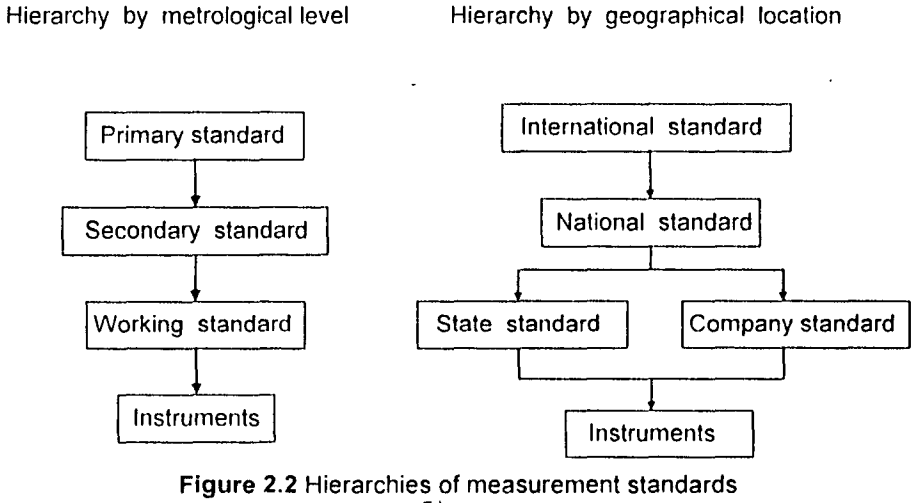


Figure 2.2 Hierarchies of measurement standards

standard. On other hand as pointed out earlier, the kilogram maintained by most countries as a national primary standard of mass is only a secondary standard in the metrological hierarchy of standards. Usually the national hierarchy scheme is incorporated in the metrology law of the country.

A measurement standard recognised by international agreement to serve internationally as the basis for assigning values to other standards of the quantity concerned is known as an *international standard.*

The primary reason for establishing a hierarchy scheme is to minimize the use and handling of the higher level standards and thus to preserve their values. Thus the primary, secondary and working standards are graded in uncertainty, the primary standards having the best uncertainty and the working standards the worst uncertainty. Figure 2.2 depicts the two hierarchies of measurement standards.

2.2.10 Traceability

The concept of traceability is closely related to the hierarchy of standards. For a particular measurement standard, or measuring instrument, *traceability* means, that its value has been determined by an *unbroken chain of comparisons* with a series of higher level standards with *stated uncertainties*. The higher level standards may be national standards maintained in a given country or international standards maintained by the International Bureau of Weights and Measures (BIPM) or other any other laboratory.

Recently this fundamental definition has been modified by the addition of a time requirement for the comparisons. It is true that if the comparisons are widely separated in time, traceability may be lost. For example a load cell fitted in a tensile testing machine may lose traceability after about one year from its last comparison. Thus the traceability of a test or measuring instrument depends largely on the type of instrument, the time interval from the last comparison and to some extent on the uncertainty of the instrument. Due to these reasons laboratory accreditation bodies such as the United Kingdom Accreditation Service (UKAS) and National Association of Testing Authorities (NATA) of Australia have formulated specific guidelines for traceability of measurement standards and test & measuring equipment used in laboratories seeking accreditation.

2.2.11 Test Uncertainty Ratio (TUR)

Calibration of test & measurement equipment is always done against a higher level measurement standard, usually a working standard. The ratio of the *uncertainty* (See Chapter 9) of the test item to that of the measurement standard used in the calibration is known as the test uncertainty ratio. In most calibrations a TUR of at least 1:5 is used, though in some circumstances, especially when the test item has a relatively small uncertainty a lesser TUR (1:2 or sometimes 1:1) has to be used. Nowadays it is more usual to determine the TUR as the ratio of the combined uncertainty (uncertainty budget) of the result obtained by the measurement standard to that obtained by the test item.

Let us look at an example. Say a pressure gauge of 0 to 1500 kPa (absolute) range is to be calibrated to an uncertainty of ± 100 Pa. With a TUR of 1:5, the measurement standard to be used for this calibration should have an uncertainty of not more than 100/ 5 Pa. i.e. ± 20 Pa. A working standard dead weight pressure tester having an uncertainty of less than ± 20 Pa would meet the criterion.

2.2.12 Resolution, discrimination and sensitivity

The *resolution, discrimination* and *sensitivity* of an instrument are closely related concepts. The resolution of a measuring instrument is the smallest difference between two indications of its display. For analog instruments this is the smallest recognizable division on the display. For example if the smallest graduation on a thermometer corresponds to 0.1 °C, the resolution of the thermometer is 0.1 °C. For a digital displaying device, this is the change in the indication when the least significant digit changes by one step. e.g The resolution of a weighing balance indicating to two decimal places in grams is 0.01 g.

Discrimination on the other hand is the ability of an instrument to respond to small changes of the stimulus. It is defined as the largest change in a stimulus that produces no detectable change in the response of the measuring instrument. For example if a Hg in glass thermometer is used to measure the temperature of an oil bath whose temperature is rising gradually, the smallest temperature change able to be registered by the thermometer will be its discrimination. This will not necessarily be equal to the resolution of the instrument. Generally in a good quality instrument the discrimination should be smaller than its resolution.

Sensitivity of an instrument is the numerical quantity that represents the ratio of the change in response to that of the change in the stimulus. This usually applies to instruments that do not have an output or response in the same units as that of the input or stimulus. A common example in a metrology laboratory is the equal arm balance. The input (stimulus) to the balance is the difference of mass between the two pans. The output is the angle of inclination of the balance beam at rest. Thus to relate the mass difference corresponding to a change in the angle of inclination of the balance beam, we need to determine the sensitivity of the balance. In the case of beam balances this is known as the sensitivity reciprocal.

2.2.13 Tolerance

Tolerance is the maximum allowable deviation of the value of a material measure, or the indication of a measuring instrument. In most cases tolerances are specified by national regulations or standard specifications. For example the OIML International Recommendation RI 111 gives tolerances for weights of different classes used for metrological purposes. (See Table 4.1)

2.2.14 Repeatability of measurements

The repeatability of a measuring instrument or measurement operation is defined as the closeness of the agreement between the results of successive measurements carried out under the same conditions of measurement within a relatively short interval of time. The repeatability conditions include the measurement procedure, the observer, the environmental conditions and location. Repeatability is usually expressed quantitatively as a standard deviation of the measurement result.

A familiar example is the repeatability of a weighing balance, which is determined by weighing a mass a number of times under similar conditions within a short interval of time. The standard deviation of the balance indications is expressed as the repeatability of the balance. A detailed procedure is given in Chapter 4.

2.2.15 Reproducibility of measurements

The reproducibility of a measurement process is the closeness of the agreement between the results of a measurement carried out under changed conditions of measurement. The changed conditions may include, the principle of measurement, the method of measurement, the observer, the measuring instrument, the reference standards used, location where the measurement is performed etc.

Reproducibility is rarely computed in metrology, though this concept is widely used and very useful in chemical and physical testing. Usually repeatability and reproducibility of a test procedure are determined by conducting a statistically designed experiment between two laboratories (or two sets of conditions) and by performing variance analysis of the test results. The variance (square of the standard deviation) attributable to variation within a laboratory (or set of conditions) is expressed as repeatability and that between the laboratories is expressed as reproducibility. These experiments are usually known as R&R (Repeatability & Reproducibility) studies.

3 Dimensional measurements

3.1 Introduction

Measurement of length, angle, flatness and surface roughness are described in this chapter. Calibration of instruments belonging to these areas is given in Chapter 10.

3.2 Length measurements

3.2.1 Primary standard

The metre has had a number of definitions since its original definition as one-ten millionth part of the meridian quadrant. When the metre convention was signed in 1875 it was defined as the distance between two marks made on a platinum iridium bar maintained at the BIPM. This standard is now only of historical importance.

The modern primary standard for length is the iodine stabilized helium neon laser. The frequency of this laser (f) is related to the wavelength of light (λ) through the relation,

$$c = f\lambda \qquad (3.1)$$

Where c = 299 792 458 m/s is the value assigned to the velocity of light by the definition of the meter. Length units are realised by incorporating the laser in an interferometer.

The frequency of the laser can be realised to an overall uncertainty of 1 part in 10^9. The frequency of the primary laser is disseminated to stabilized laser interferometer systems used for measurement of length and displacement.

3.2.2 Secondary and working standards

Helium neon lasers available commercially are widely used as the secondary standard for length. Usually these are used in combination with a measuring machine, gauge block comparator or co-ordinate measuring machine. In addition a range of other artifacts such as gauge blocks, length bars, line standards and tapes are used as working standards.

a) Linear measuring machine

A schematic diagram of a linear measuring machine is shown in Fig 2.1. A measuring machine is a linear measuring instrument having a solid base and machined sliding surfaces. In the version known as the universal measuring machine linear measurements can be made in two axes perpendicular to each other.

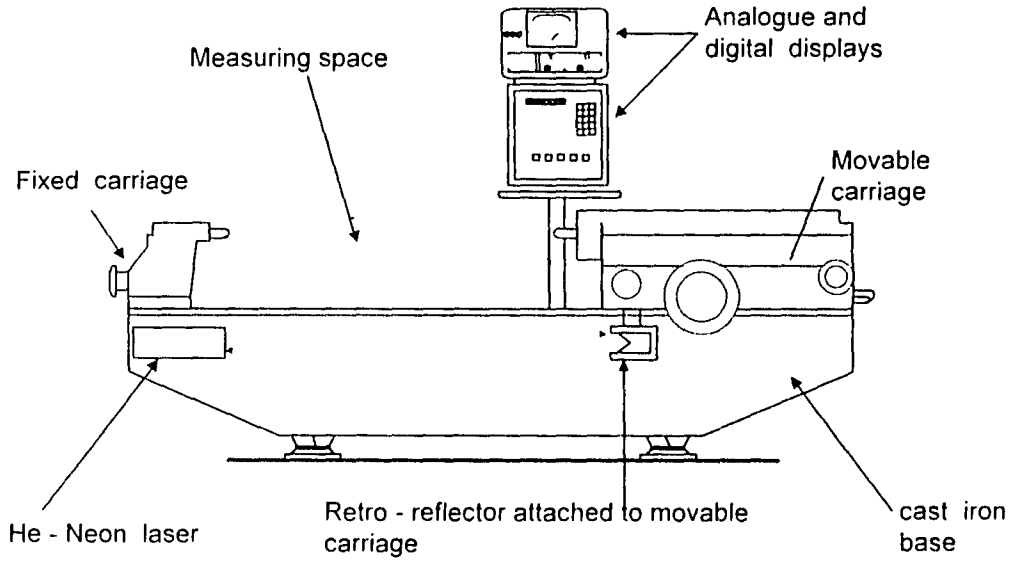


Figure 3.1 Linear Measuring machine

Fixed and movable carriages are mounted on the sliding surfaces. In the older versions a line standard was incorporated in the machine. In modern versions a helium neon laser is mounted on the base as shown in Figure 3.1. A retro reflector is mounted on the movable carriage. The laser beam is aligned so that it is parallel to the longitudinal axis of the machine. Interference takes place between the direct beam emitted by the laser and the beam reflected by the retro reflector. By counting interference fringes, the distance between the reference plane of the laser cavity and the retro reflector is computed accurately.

Usually the fringes are counted electronically and converted to length units. An accurate value of the refractive index of air is required for this purpose. The temperature, pressure and relative humidity of ambient air are measured to calculate the refractive index. The frequency of the laser is obtained by comparison with a primary standard helium neon laser.

Measuring machines having resolution of 0.1 μm and relative uncertainties of the order of 0.25 ppm are commercially available.

b) Gauge blocks

Gauge blocks were originally produced by C.E. Johansson of Sweden and are known as end standards as the reference surfaces of the block are its ends. Gauge blocks are available having rectangular or square sections. They are also available as short blocks (upto 100mm) and long blocks (upto 1000 mm). Usually gauge blocks are available as sets consisting of a number of blocks enabling the building up of any length between 0.5 mm and 200 mm in steps of 0.0005 mm. A set of gauge blocks ranging from 2 mm to 100 mm consisting of 112 blocks is shown in Fig 3.2.

Figure 3.2-Set of gauge blocks

Wringing of gauge blocks

Two Gauge blocks can be wrung together to form an extended length. Wringing is done by bringing the surfaces of two blocks into contact and pressing lightly until they adhere to each other. The wringing phenomenon is believed to be due to the action of molecular forces at the interface. Very recent research indicates that the presence of a fluid (oil) film in the interface to be responsible for the wringing action. The separation is done by carefully sliding one block parallel to the plane of adhesion. When two blocks are wrung together a contact layer of unknown thickness is formed between the two surfaces. For most practical purposes, the thickness of this layer can be neglected. Before wringing gauge blocks together, their faces should be wiped free from dust and examined for burrs.

Building up a size combination of gauge blocks

The gauges to be used for building up a size combination are determined by the following method:

The micrometer (0.001 mm) block is taken first, followed by the hundredth, tenth and millimetre blocks.

Example-To build up 108.455 mm from a 112-block set,

1 st block	1.005
2 nd block	1.05
3 rd block	1.40
4 th block	5
5 th block	100

Documentary standards

The following international standards specify the dimensional and other requirements of gauge blocks:

ISO 3650:1999 – Gauge blocks

OIML RI 30:1981 – End standards of length (Gauge blocks)

Also a number of national standards available are listed in the bibliography.

Critical characteristics

A number of important parameters of gauge blocks are defined in the international standards mentioned above. A summary of these are given below:

Length of a gauge block

The length of a gauge block is the perpendicular distance between any particular point of one measuring face and the plane surface of an auxiliary plate of the same material and surface texture on which the opposite measuring surface of the gauge block has been wrung. The length includes one wringing film. This definition is illustrated in Figure 3.3.

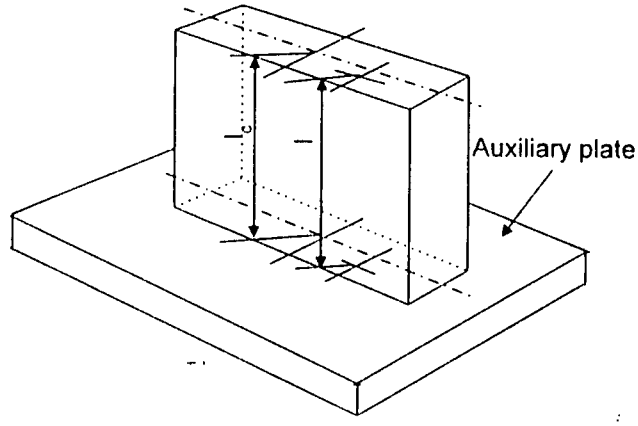


Figure 3.3 Central length and length at any point of a gauge block (Source :ISO 3650)

Central length

The central length is a specific case of the length defined in the previous paragraph. The central length is the length taken at the center point of the free measuring face.

Deviation from nominal length

The difference between the nominal length and the length at any point is the deviation from nominal length at any point, see Figure 3.4.

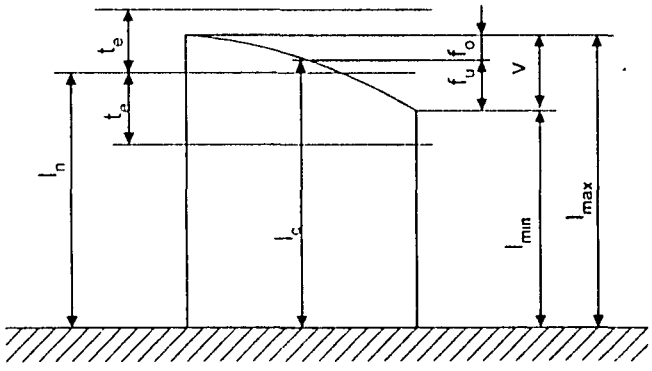


Figure 3.4-Geometrical properties of gauge blocks (Source: ISO 3650)

Variation in length

The variation in length is the difference between the maximum length (l_{max}) and the minimum length (l_{min}) of a given gauge block.

Deviation from flatness

The distance between two parallel planes enclosing all points of a measuring face is defined as the deviation from flatness. This is shown in Figure 3.5.

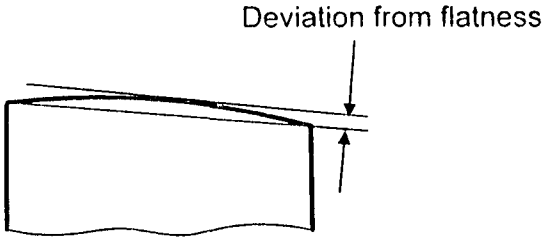


Figure 3.5-Deviation from flatness (Source : ISO 3650)

Parallelism & perpendicularity of datum surfaces

The parallelism between the measuring faces and the perpendicularity of a measuring face with a side face are important parameters and are usually specified.

Surface finish

Surface finish of the measuring faces is important from the point of view of wringing quality so that the blocks wring readily. Fine scratches without burrs are acceptable provided they do not impair the wringing quality.

Dimensional stability

The stability of the length between the measuring surfaces of a gauge block over an extended period of time is an essential requirement. This is of the order of 0.02 μm per year for blocks of grade K and 0 and 0.05 μm for blocks of grade 1 and 2.

Material

Gauge blocks are made from hardened high grade alloy steel, zirconia ceramic or tungsten carbide. The hardness and long term stability of the material are important properties. Gauge blocks made of steel should have a hardness of not less than 800 HV 0.5.

Blocks made from zirconia ceramic have excellent properties. The wringing characteristics are very good. They are also very tough and have very good wear resistance upto three times that of tungsten carbide, low thermal conductivity, excellent resistance to corrosion and light weight. The coefficient of thermal expansion is close to that of steel (9.5×10^{-6} /°C).

Tungsten carbide has also been used extensively as a material for manufacture of gauge blocks. Gauge blocks made of tungsten carbide have very good wringing characteristics and good resistance to corrosion. The co-efficient of thermal expansion (4.23×10^{-6} /°C) is approximately half that of steel.

The lowest cost and most popular material for gauge blocks is hardened alloy steel. The major disadvantage of steel blocks is their susceptibility to corrosion.

Grades of gauge blocks

ISO 3650 specifies four grades of gauge blocks :

Grade K, Grade 0, Grade 1 and Grade 2

The grading is based on the deviation of length at any point from the nominal length as well as the tolerance for the variation in length. Grade K is specified as calibration grade for use as the reference standard for calibration of the other grades. Grade K gauge blocks will usually require calibration against a primary or secondary standard gauge block interferometer.

ISO 3650 grading system is given Table 3.1.

Care and use of gauge blocks

General care

The greatest care should be exercised in protecting gauge blocks and their case from dust, dirt and moisture. When not in actual use, the blocks should always be kept in their case and the case should be kept closed. The blocks should be used as far as possible in an atmosphere free from dust. In the case of steel blocks, care should be taken that the blocks do not become magnetized or they will attract ferrous dust.

Preparation before use

If the blocks are new or have been covered with a protective coating after being last used, most of this coating should be removed with an appropriate solvent (Iso propyl or methyl alcohol). The measuring faces should finally be wiped with a clean chamois leather or soft linen cloth. This wiping should be carried out in every instance before a block is used, irrespective of whether it has been stored coated or merely returned temporarily to the case uncoated. It is, however, undesirable to aim at removing all traces of grease since a very slight film of grease is an aid to satisfactory wringing.

Care in use

Handling the lapped faces with bare hands should be avoided to reduce the risk of leaving finger prints. Unnecessary handling of the blocks in use should be avoided as they take up the heat of the hand. If the blocks have been handled for some time they should be allowed

Table 3.1 Limit deviations of length and tolerances from nominal length of gauge blocks (Source: ISO 3650)

Nominal length	Grade K		Grade 0		Grade 1		Grade 2	
	Limit deviation of length at any point from nominal length	Tolerance for the variation in length	Limit deviation of length at any point from nominal length	Tolerance for the variation in length	Limit deviation of length at any point from nominal length	Tolerance for the variation in length	Limit deviation of length at any point from nominal length	Tolerance for the variation in length
l_n	$\pm t_e$	t_v	$\pm t_e$	t_v	$\pm t_e$	t_v	$\pm t_e$	t_v
mm	µm	µm	µm	µm	µm	µm	µm	µm
$0.5 \le l_n \le 10$	0.2	0.05	0.12	0.1	0.2	0.16	0.45	0.3
$10 < l_n \le 25$	0.3	0.05	0.14	0.1	0.3	0.16	0.6	0.3
$25 < l_n \le 50$	0.4	0.06	0.2	0.1	0.4	0.18	0.8	0.3
$50 < l_n \le 75$	0.5	0.06	0.25	0.12	0.5	0.18	1	0.35
$75 < l_n \le 100$	0.6	0.07	0.3	0.12	0.6	0.2	1.2	0.35
$100 < l_n \le 150$	0.8	0.08	0.4	0.14	0.8	0.2	1.6	0.4
$150 < l_n \le 200$	1	0.09	0.5	0.16	1	0.25	2	0.4
$200 < l_n \le 250$	1.2	0.1	0.6	0.16	1.2	0.25	2.4	0.45
$250 < l_n \le 300$	1.4	0.1	0.7	0.18	1.4	0.25	2.8	0.5
$300 < l_n \le 400$	1.8	0.12	0.9	0.2	1.8	0.3	3.6	0.5
$400 < l_n \le 500$	2.2	0.14	1.1	0.25	2.2	0.35	4.4	0.6
$500 < l_n \le 600$	2.6	0.16	1.3	0.25	2.6	0.4	5	0.7
$600 < l_n \le 700$	3	0.18	1.5	0.3	3	0.45	6	0.7
$700 < l_n \le 800$	3.4	0.2	1.7	0.3	3.4	0.5	6.5	0.8
$800 < l_n \le 900$	3.8	0.2	1.9	0.35	3.8	0.5	7.5	0.9
$900 < l_n \le 1000$	4.2	0.25	2	0.4	4.2	0.6	8	1

to assume the prevailing temperature of the room before being used for test purposes. This is particularly important in the case of the larger sizes. When the highest accuracy is required, a test room with a controlled temperature of 20 °C becomes necessary, but for

ordinary purposes, provided the blocks and workpiece are of the same material, a sufficient degree of accuracy can be obtained if time is allowed to permit both to assume the prevailing temperature of the room.

Damaged gauges

Damage to the measuring faces is most likely to occur on the edges. Slight burrs may be removed with care by drawing an Arkansas type stone lightly across the damaged edge in a direction away from the, measuring face of the standard. Any measuring face so treated should, be thoroughly cleaned before wringing. A standard with a damaged measuring face should preferably be returned to the manufacturer for the surface to be restored.

Care after use

Immediately after use each block should be wiped clean and be replaced in its proper compartment in the case. It is particularly important to remove any finger marks from the measuring faces. If the blocks are used infrequently they should be coated with a suitable corrosion preventive before being put away. The preparation should be applied to the measuring faces with a clean piece of soft linen. A brush should not be used as this may aerate the preparation and moisture in the air bubbles so formed can cause rusting of the faces.

3.2.3 Length measuring instruments

A brief description of length measuring instruments suitable for different purposes is given in this section.

a) Surface plate

The surface plate is an essential item for dimensional measurements both in the laboratory and in the factory. Usually all linear measurements are taken from a reference plane. The surface of a surface plate is used for this purpose.

Traditionally the flat surface plate was made from cast iron either as a freestanding table or suitable for mounting on a bench. Both had their upper surface hand scraped to a very high degree of flatness. The grade of surface plate is determined by the degree of flatness, which is defined as the distance between two parallel planes containing all the points of the surface. In recent years natural rock materials have become increasingly popular and granite plates have almost entirely replaced the cast iron plate.

Granite is twice as hard as cast iron and changes in temperature has only a minimal effect on its surface contour. The fine grain structure of well-seasoned granite ensures a surface largely free from burrs and protrusions and a high degree of flatness over a relatively long period of time.

Granite surface plates are available in sizes ranging from 300 mm x 300 mm x 100 mm to 2000 mm x 1500 mm x 300 mm. The best grade plates have a flatness ranging from 5 μm to 15 μm.

b) Outside micrometer

An outside micrometer is used to measure the thickness or diameter of hard materials. Outside micrometers are available with a measuring range of upto 2 m and 0.01 mm resolution. However, the range of the measuring head itself rarely exceeds 25 mm, and if the micrometer is required to measure large dimensions, it must be used as a comparator set to either zero position or preferably to a dimension near the work piece size, using an end bar. Large size micrometers are usually available as a set, consisting of the frame, micrometer heads and setting bars.

A wide variety of these micrometers are available for different applications. Common types are:

With dial indicator, with LCD digital indicator, snap micrometer, dial snap micrometer, screw thread micrometer, tube micrometer, point micrometer and sheet metal micrometer.

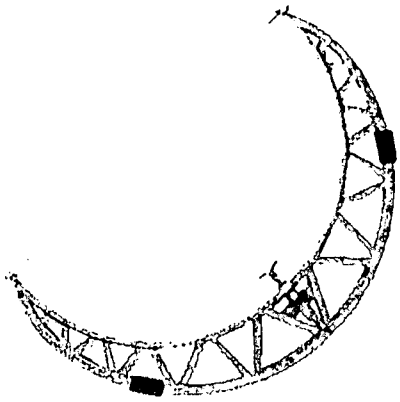


Figure 3.6-Outside micrometer of 1 meter range (Source : Mitutoyo Corp., Japan)

c) Inside micrometer

Micrometers used for internal measurements (internal diameters of cylinders and similar objects) are known as inside micrometers. Instruments with jaws range upto about 300 mm with a micrometer head of range 25 mm. Those exceeding a range of 300 mm are in the form of a cylinder with the measuring head at one end. Both types are available with a resolution of 0.01 mm. Inside micrometers having a measuring range of upto 5000 mm with micrometer head range of 50 mm are available. Cylindrical type inside micrometers are invariably supplied with sets of extensions that permit one head to cover a wide measuring range.

d) External & internal Vernier calipers

Vernier calipers are used to measure external and internal diameters of objects and internal dimensions of cylinders and grooves. A range of sizes as well as a variety of types from the simple stainless steel type to those fitted with digital liquid crystal displays, battery or solar powered are available. Also, some types employ carbon fiber reinforced plastics in the beam and jaws to make them light and yet strong. Most types are available upto a measuring range of 1000 mm with 0.01 mm resolution.

e) Dial gauge

A frequently used instrument for measurement of small deviations relative to a datum surface is the dial gauge. A dial gauge consists of a spindle that moves inside a cylindrical tube. The linear motion of the spindle is translated into rotation of a shaft by the use of a rack and pinion mechanism. A pointer attached to the end of the shaft is made to move over a graduated circular dial.

In a different design, known as the lever type, the spindle is replaced with a stylus. The up and down motion of the stylus is translated into the rotary motion of the pointer.

A wide variety of dial gauges of different ranges, usually upto about 100 mm and best resolution of 0.002 mm are available.

f) Bore gauge

A bore gauge is an instrument used for the measurement of internal diameter of cylinders. A bore gauge consist s of a cylindrical tube from which three prongs extend symmetrically. A micrometer head is attached to the cylinder and connected to the prongs internally. The movement of the micrometer spindle makes the prongs extend or contract. To measure the internal diameter of a cylinder at a given plane, the bore gauge is inserted into the cylinder until the prongs are positioned at the required plane. The micrometer spindle is rotated until the three prongs are in contact with the surface. The reading of the instrument gives the mean diameter from the three contact points.

Bore gauges are available in a wide variety of sizes and can be read to 0.001 mm.

g) Depth gauge

The depth gauge is another popular variation of a linear measuring instrument with a vernier reading and specialized anvils. The depth gauge is used to measure depth of holes and steps.

h) Height gauge

The height gauge could be described as a vernier caliper fixed to a firm base. In contrast to the vernier caliper the height gauge has only one moving anvil connected to a vernier scale. A column having a fixed scale is mounted so that the axis of the column is perpendicular to the reference plane of the base. The motion of the anvil up and down the fixed scale allows vertical distances to be measured accurately. Usually a height gauge is mounted on a surface plate for measurement of vertical distances.

i) Tapes

Steel and fabric tapes are used for measurement of lengths in excess of one metre. Usually steel tapes are available in lengths of 50 m, 100 m and up to about 500 m. Fabric tapes are available up to lengths of 100 m.

j) Laser measuring systems

A number of linear measuring systems using laser interferometry are available. In most systems a helium neon laser operating at 633 nm is used as the coherent source of light. These systems have very good resolution and accuracy as well as other features such as non-contact measurement capability. Also data acquisition and analysis are conveniently handled by either inbuilt processors and programs or external hardware and software. Laser interferometry systems have measuring ranges of upto 30 meters with resolution of a few micrometers.

Instruments based on the principle of simple interference of a direct and reference beam of light are excellent instruments for linear measurements. However they require an accurate value for the refractive index of air to compute the length from the measured phase difference of the two interfering beams. Though this is relatively easy under laboratory conditions, in the field or in a factory the same accuracy can not be obtained due to the variation of ambient temperature, humidity and pressure under field conditions.

A laser grating interferometer is less susceptible to variation of refractive index of air and is an ideal instrument for use in industrial situations. Grating interferometers measure length using the interference of two light beams diffracted on a diffraction grating and subsequent evaluation of the phase difference. Linear encoders fitted to many linear measuring instruments is based on this principle. Linear encoders incorporating laser-grating interferometers have a maximum measuring range of about 1500 mm with an uncertainty of $\pm$ 10 μm.

A laser scan micrometer using the principle of scanning laser interferometry is shown in Figure 3.7. This type of instrument is capable of measuring workpieces that are brittle or soft that may suffer dimensional change due to the measuring force. Also these instruments easily handle workpieces that are at a raised temperature and difficult for measurement by conventional instruments.

Laser scan micrometers are available with measuring ranges of 2mm to 120 mm and resolutions of 0.01 μm to 0.1 μm. Repeatability of these instruments is of the order of $\pm$ 2 μm.

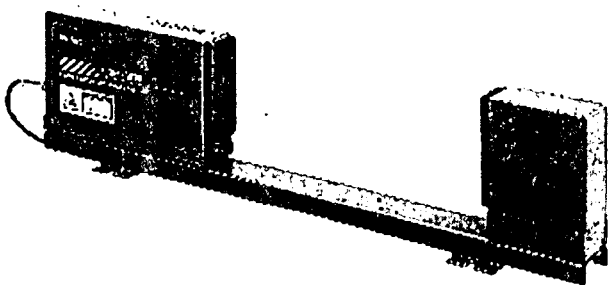


Figure 3.7-Laser scan micrometer (Source: Mitutoyo Corp., Japan)

k) Coordinate measuring machine (CMM)

A coordinate measuring machine (CMM) is a general-purpose, high-speed instrument used for measuring small to medium sized workpieces. They offer high measurement accuracy and excellent measuring efficiency. Most modern instruments are automated with in-built or external computers and are relatively simple to operate.

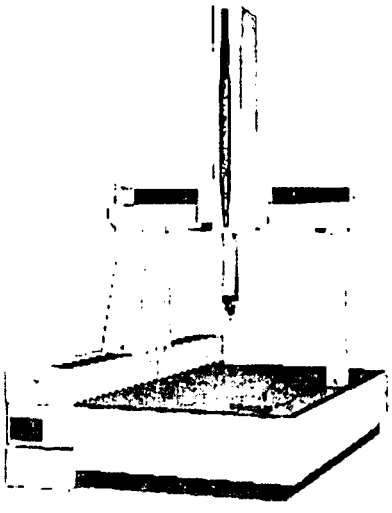


Figure 3.8-Co-ordinate measuring machine (Source: Mitutoyo Corp. Japan)

The essential components of a coordinate measuring machine are a work table and carriages movable in three mutually perpendicular axes (X, Y and Z). The main carriage is movable along the longitudinal axis (X axis) of the work table. A secondary carriage (Y axis) is movable on the cross bar (bridge) of the X-axis carriage and a vertically mounted spindle constitutes the Z-axis. A probe is attached to the end of the Z-axis spindle.

The motions of the three carriages in X (back and forth), Y (right and left), and Z (up and down) directions enables the probe to be placed at any point within the measuring volume of the instrument. Precise linear encoders, installed on each axis, measure the probe displacement. The positional data obtained at each measured point is output to a computer for two or three-dimensional measurement including determination of point coordinates, dimensions, and contours. These abilities are especially useful when measuring bulky workpieces that are hard to handle, and when making multi-planar measurements of complicated workpieces.

Coordinated measuring machines are best suited for measuring fabricated products such as:

Moulds for pressing, die casting, injection moulding, and precision castings,

Moulded products before and after machining,

Prototypes made on numerically controlled machine tools, and

Machined parts

Advantages of coordinate measuring machines

Coordinate measuring machines have the following advantages over conventional measuring systems:

a) The coordinates of any point on a workpiece are determined by simply placing the probe tip in contact with it.

b) All work piece faces, other than the bottom, may be measured provided the workpiece is correctly mounted.

c) Highly precise measurements can be performed with minimal training. In addition, the time required for workpiece set up and measurement is reduced.

d) Datum (reference) points can be specified as required.

e) A data processing unit instantly determines and prints dimensions, coordinates and contours of workpieces, and then compares the measurements with their design values and tolerance limits, resulting in a great reduction in time for measurement data analysis.

The accuracy of measurement of a coordinate measuring machine depends on the nominal dimensions of the workpiece. Typical accuracies and uncertainties of a commercially available instrument are given below:

Linear displacement accuracy: $3 + 3L/1000$ μm

Axial length measuring accuracy: $3 + 3L/1000$ μm

Volumetric length measuring accuracy: $3.5 + 3.5L/1000$ μm

Repeatability ± 6 μm

L- Nominal length in meters

3.2.4 Linear measurement errors and their correction

a) Effect of temperature

Temperature of the environment is a critical influence factor for dimensional measurements. The recommended standard temperature is 20 °C. However even in a laboratory with temperature controlled at 20 °C, the workpiece temperature may be slightly different. Therefore the temperature of the workpiece is measured using a calibrated thermometer and the dimensional values measured are corrected using the thermal expansion co-efficient of the material.

The change in length (δL) of a test item due to a change in temperature is given by the following equation:

$$\delta L = L.\alpha.\delta t \qquad (3.2)$$

Where,

L - original length of the test item

α - linear expansion co-efficient of the material

δt - change in temperature

The linear thermal expansion co-efficients of several materials are given in Table 3.2. When the measuring instrument and the test item being measured are of two different materials a differential expansion results. Corrections are required for these effects.

Table 3.2 Linear thermal expansion co-efficients of materials

Material	Linear expansion co-efficient , /°C
Cast iron	$9.2\text{-}11.8 \times 10^{-6}$
Steel	11.5×10^{-6}
Chromium steel	$11\text{-}13 \times 10^{-6}$
Nickel chromium steel	$13\text{-}15 \times 10^{-6}$
Copper	18.5×10^{-6}
Bronze	17.5×10^{-6}
Gunmetal	18.0×10^{-6}
Aluminium	23.8×10^{-6}
Brass	18.5×10^{-6}
Nickel	13.0×10^{-6}
Iron	12.2×10^{-6}
Nickel steel	12.0×10^{-6}
Invar (36 % Nickel)	1.5×10^{-6}
Gold	14.2×10^{-6}
Glass (Crown)	8.9×10^{-6}
Glass (Flint)	7.9×10^{-6}
Ceramics	3.0×10^{-6}

b) Deformation

Deformation is the second most important influence factor. Mainly three effects cause deformations:

a) Due to force exerted on the test piece by the measuring instrument
b) The method of support used for the test item
c) The method of support of the measuring instrument

c) Force exerted by the measuring instrument

The deformation (within the elastic limit) due to the force exerted by the measuring instrument is estimated from:

$$\Delta L = \frac{F.L}{E.A} \qquad (3.3)$$

Where,

F - measuring force

L -length of test item

E -Young's modulus

A - cross sectional area of the test item

d) The method of support of the test item

When a test item is supported on a flat surface such as a surface plate the unevenness of the plate will affect the measurements to be performed. Due to these reasons and for precise

measurements test items are generally supported on knife edges or cylinders. The knife edges or cylinders are placed symmetrically in relation to the length of the test item.

Airy points

At airy points the two vertical edges of an end standard remains parallel to each other, Figure 3.9.

The distance between the Airy points is given by:

$$d = \frac{L}{\sqrt{n^2 - 1}} \qquad (3.4)$$

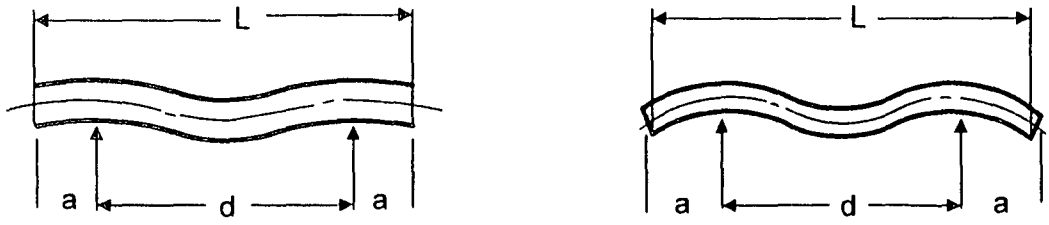
Where

L -length of the test piece

d -distance between Airy points

n -number of supports

For two point support, d = 0.5774 L and a = 0.2113 L



Airy points Bessel points

Figure 3.9 Airy and Bessel points of support

Bessel points

When a long test item is supported at Bessel points the contraction of the center line of the item due to its own weight is a minimum, Figure 3.9. This method of support is most suitable for calibration of long standard scales.

The distance between Bessel points is 0.5594 L and a = 0.2203L.

e) Abbe error

Abbe error arises when the axis of the instrument or standard being used for the measurement does not coincide with the axis of the test item being measured. The deformation of the measuring arm of a caliper type micrometer through an angle θ gives rise to an error in length of $d\bar{\theta}$

e.g if θ= 1 minute and d= 30 mm,

Abbe error = 30 x 1/ 3000 = 10 μm

f) Parallax error

Parallax errors occur when viewing a pointer against a graduation mark as in the case of a dial indicator or viewing graduations which are in different planes as in the case of a micrometer sleeve and thimble. In these situations it is best to observe normal to the plane of the graduations as far as practicable.

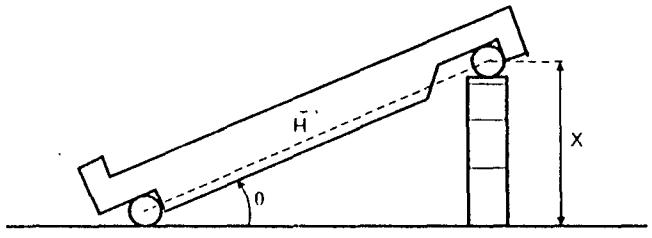
3.3 Measurement of angle

3.3.1 Angle standards

a) Sine bar

A sine bar consists of a flat rectangular section to which two rollers are rigidly attached. The distance between the rollers is very important and determines the accuracy of the instrument. This distance is usually in multiples of 50 mm for ease of calculation.

The method of using a sine bar to generate an angle is shown in Figure 3.10.The vertical dimension of the triangle is formed by gauge blocks of such a length that division by the length of the sine bar gives the sine of the required angle.



$$\sin\theta = \frac{X}{H}$$

Figure 3.10-Use of a sine bar to generate an angle

This method is difficult to use as a direct means of measurement but is used for generation of accurate angles. A useful development of the sine bar is the sine table, which is formed by increasing the width of the sine bar. This provides a plane, on which the workpiece can be mounted. A further development is the compound sine table, which is effectively two sine tables mounted at right angles on top of each other. A complex workpiece can be mounted on the upper sine table so that a chosen surface is made parallel to the base plane.

b) Indexing table

The most popular instrument for angle generation and measurement is the indexing table. The indexing table is a rotating table made by dividing a circle accurately. Both motor driven and hand driven types are available. In the most precise instruments angles can be generated and measured to the nearest second.

c) Precision polygon

Precision polygons are made from hardened and stabilized steel or glass. They have lapped or polished working surfaces normal to equal divisions of a circle. Polygons with 12 faces at 30 ° intervals or 72 faces at 5 ° intervals are normally available. Precision polygons are mainly used for calibrating indexing tables and dividing heads. In the calibration of an indexing table the polygon is mounted on the table with its axis coincident with the axis of the table and the table is rotated through the angle of the polygon. By focusing an autocollimator on two adjacent working faces of the polygon the deviation of the rotation of the table in relation to the angle of the polygon is determined.

d) Angle gauge

An angle gauge is a block of hardened steel with two lapped working surfaces at a precise angle to each other. They are available in sets and can be wrung together to form angles when used together with a precision square block.

A system of angle gauges invented by Tomlinson of the National Physical Laboratory of the United Kingdom has twelve angle gauges of nominal values

3,9,27 seconds

1,3,9,27 minutes

1,3,9,27,41 degrees

and a single square block. This set provides angles upto 360 ° with an interval of 1.5 degrees. The angle gauges are approximately 75 mm long and 16 mm wide and can be wrung together to form either additive or subtractive combinations.

e) Autocollimator

An important instrument used for angle measurement is the autocollimator. A collimating lens is used to focus a parallel beam of light onto a reflecting surface kept normal to the incident beam of light and the reflected beam is focused onto a measuring eye piece. If the reflector is inclined at a small angle $\delta\theta$ to the normal, the reflected beam is inclined at an angle of $2\delta\theta$ to the transmission path and is measured by a scale incorporated in the microscope eyepiece. An autocollimator in combination with a precision polygon is used to calibrate indexing tables.

3.4 Measurement of form

3.4.1 Flatness and Optical flats

An optical flat is made from pyrex glass, quartz or from stainless steel. The surface is polished to be within a few nanometers and to practically zero waviness.

The hand-held optical flat is the traditional tool for monitoring the quality of plane surfaces. It is typically flat to one-twentieth of the wavelength of visible light or 25 nanometers. In the past 20 years, laser-based interferometers have become important measuring tools in the optical shop and precision optical flats play a central role in the operation of these instruments.

As a hand-held reference tool, the optical flat is brought into contact with the surface whose flatness is to be measured, known as the "surface under test." If the surface under test is not flat, then some regions of the two surfaces will not touch each other.

Deviations from flatness of only a few nanometers can be detected by using a monochromatic source of light to shine on the two surfaces. Where the two surfaces are not in intimate contact, air gaps are formed and Newton's Rings can be seen

Newton's Rings are bands of light and dark that crosses the region under test. They form a contour map of the microscopic gaps between the surfaces. . The thickness of the gap is estimated by counting the number of rings (or fringes) formed.

In an interferometer designed for testing flat surfaces, a single beam of light is divided into two beams. One beam serves as a reference by illuminating an optical flat, and the second is used to illuminate the surface under test. The wavefronts in each beam take on the shape of the surfaces off which they reflect. When the two beams are recombined, the wavefronts add in a way that shows how the shape of the surface under test deviates from the shape of the reference surface.

Since certain glasses, such as Pyrex®, have very small coefficients of thermal expansion, a Pyrex optical flat can maintain its thickness and its precise flatness over a larger temperature range than metal. Therefore, an optical flat can serve as a very stable source of calibration, under variable environmental conditions, for precision measuring tools such as coordinate-measuring machines.

3.4.2 surface roughness and waviness

The assessment of surface texture of the earliest metalwork was qualitative and depended essentially on its reflectivity. The development of more refined techniques of production and more exacting design requirements, increasingly accurate measuring methods as well as the

desire to understand better the relationship between the surface condition and the functional characteristics of components led to demands for quantitative assessment methods rather than subjective or qualitative assessments.

Surface texture is generally examined in plan view with the aid of optical and electron microscopes, in cross section normal to the surface with stylus instruments, and in oblique cross sections by light sectioning methods. In the case of very rough surfaces such as those found in castings and sintered materials optical interference and stylus methods cannot be applied.

Surface roughness is deemed to include all irregularities which recurring many times across the surface tend to form a pattern or texture on it. Some definitions from BS 1134 follows:

Roughness (Primary texture)- The irregularities in the surface texture which result in the inherent action of the production process. These are deemed to include traverse feed marks and the irregularities within them in the case of machined components and sand grain marks and mold irregularities in the case of castings, Figure 3. 11.

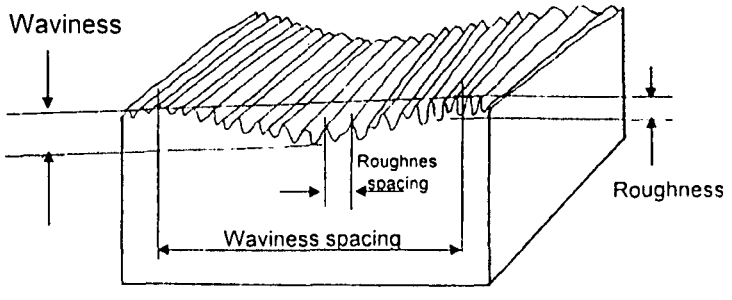


Figure 3.11 Concept of roughness and waviness

Waviness (Secondary texture)- That component of surface texture upon which roughness is superimposed. Waviness may result from such factors as machine or work deflections, vibration ,chatter heat treatment or warping strains.

Lay – The direction of the predominant surface pattern, usually determined by the production method used.

Isotropic surface : A surface which does not exhibit a pronounced lay.

Anisotropic surface : A surface with a pronounced lay.

3.4.3 Numerical assessment of surface roughness

Numerical assessment is required as an aid to describe surface irregularities and to quantify the roughness of the surface as a single numerical value. Numerical designations are useful for specification of surfaces on drawings and to aid the control of manufacturing processes although no single numerical parameter has yet been devised to describe a surface completely,

Surface topography is characterised by the types of irregularity that appear in combination and by their height, shape and spacing. The functional quality of a surface often depends both on the geometrical topography as well as on the physical or metallurgical state of the outermost layers of the material. These characterising features are determined collectively by the process of manufacture, e.g. milling, grinding, casting, turning produce surfaces characteristic of these processes.

The specification of surfaces is thus a complex matter. Numerical assessment of the topography is generally based on selected samples of the profiles of one or more cross sections of the surface. The procedure generally involves:

a) Identifying the irregularities to be measured and separating them with the aid of a filter,

b) Deriving a reference line from which to measure the selected irregularities. (Several such lines being recognized),

c) Evaluating with respect to the chosen reference line one or more of so-called 'parameters', e.g. Center line average value (CLA), maximum peak to valley height (Rt), average height, distribution of crests etc.

The irregularities to be measured can be segregated by graphical, electrical, mechanical or digital methods, each of which could be regarded as a form of a filter, It is worthwhile to examine the basic principles used in numerical assessment and the parameters generally used.

Graphical filtering is effected by limiting the length over which an individual measurement is made. Thus in Figure 3.12(a) samples of length L_1 will serve tó isolate the roughness, while in Figure 3.12(b) samples of length L_2 would include the waviness. If a straight line is drawn through each of the samples L_1 and the sections drawn with their axes in line, the profile drawn in Figure. 3.12(c) will result,-which is the original profile with the waviness filtered out.

It will be seen that for the measurement of texture of nominally random profiles

1) The sample must be long enough to be representative of the roughness at least in one locality of the surface and

2) Either short enough to exclude or long enough to include the waviness as the case may be.

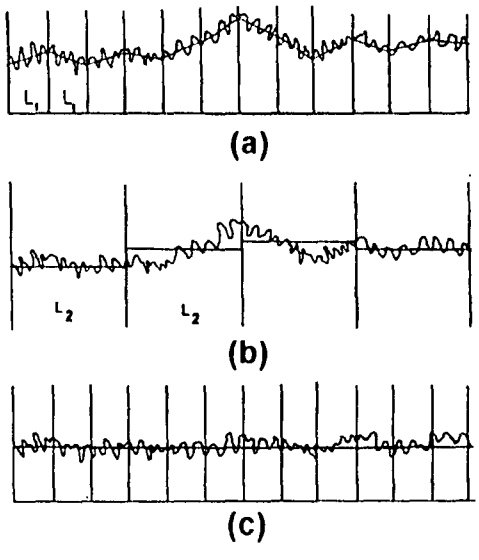


Fig 3.12-Illustration of graphical filtering

Generally a succession of individual samples is taken and averaged, the total length involved constituting what is called the traversing length. For convenience and especially to provide a basis for instrumentation a series of sampling lengths has been internationally standardised.

ISO 3274-1996, and other national standard specifications, specify the following values for the sampling lengths:

mm 0.08 0.25 0.8 2.5 8.0 25.00

Generally 3 to 10 consecutive samples are evaluated to provide a fair average for the chosen locality. Electrical filtering is very often used and is accomplished by passing an alternating current representing the profile through an electric wave filter

a) Center line average value (CLA) or Ra

A widely used parameter for quantifying surface roughness is the arithmetic average departure of the surface profile from some predetermined mean line.

The mean line is determined as the line which divides the profile into equal areas above and below the line. The usual procedure is to utilise the principle of least squares. A line is drawn through the profile such that the sum of the squares of all the deviations from it is a minimum. Areas above and below the line are then minimum and equal.

In determining the roughness of a surface a single mean line may not give a good indication of the nature of the surface. Therefore a separate mean line is used for each of the sampling lengths.

The average roughness of the surface (Ra) is then defined as the arithmetical deviation of the points in the profile from the centre line.

$$R_a = \frac{1}{L}\int_0^L y\,dx$$

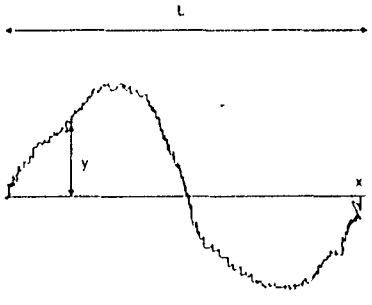


Figure 3.13- Definition of R_a and R_z values

b) Root mean square value

An alternative method of defining average roughness, is the root mean square average(RMS or R_z) obtained from the equation :

$$R_z = \frac{1}{L}\sqrt{\int_0^L y^2 dx}$$

Values of R_z are generally 10-30% higher than those for R_a. It will be noted that the value of or R_a or R_z computed in this manner depends on the value of the sample length chosen, i.e. in the case of stylus instruments the R_a value will depend on the meter cut off used .

c) Maximum Peak to valley height (R_{tmax})

The maximum peak to valley height within a given traversing length is another parameter which is used. The maximum peak to valley height within a sampling length is known as R_{tmax}. In a traversing length consisting of five sampling lengths, five consecutive peak to valley heights, R_{t1}, R_{t2}, R_{t3}, R_{t4} and R_{t5} (Fig. 3.14) are determined. R_{tmean} is defined as the average of these five consecutive values,

$$R_{tmean} = \frac{R_{t1} + R_{t2} + R_{t3} + R_{t4} + R_{t5}}{5}$$

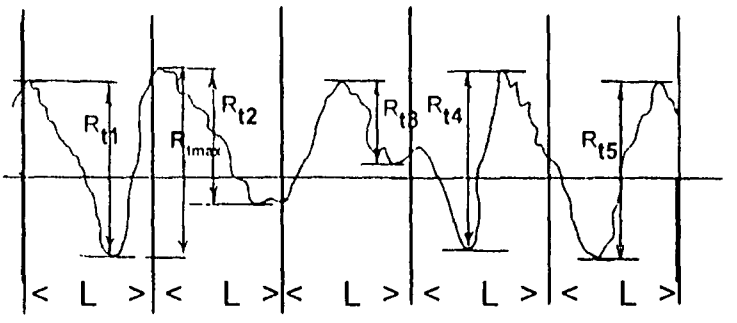


Figure 3.14–Peak to valley heights of a surface

d) Amplitude density function and skewness

If the frequency of occurrence of height x within the sampling length is plotted alongside the profile a curve known as amplitude density function is obtained. The amplitude density function is important in that information regarding the nature of the profile could be obtained from it. The skewness of the amplitude distribution curve is a measure of the asymmetry of the profile and is used to distinguish between asymmetrical profiles having equal R_a or R_q values.

Skewness will also show whether porous sintered and cast surfaces will yield a meaningful R_a value. The criterion for a good bearing surface is that it should have a negative value for skewness.

e) Average slope of the profile

Another parameter which is being increasingly used is the average slope (Δ_a) or RMS slope (Δ_q) value of the slope of the profile through its length. From this value the ratio of the actual profile length to the nominal measured length can be obtained.

$$\frac{\text{Actual length}}{\text{Nominal length}} \cong 1 + \frac{1}{2}(\Delta_a)^2$$

f) Average wavelength,

Average wavelength λ_a or RMS wavelength λ_z is a measure of the spacings between local peaks and valleys taking into account their relative amplitudes and individual spatial frequencies. Being a hybrid parameter determined from both amplitude and spacing information it is for some applications more useful than a parameter based solely on the amplitude or spacing,

$$\lambda_a = \frac{2\pi R_a}{\Delta_a} \qquad \lambda_q = \frac{2\pi R_z}{\Delta_z}$$

g) Statistical properties of surfaces

The generally irregular nature of surface topography attracts attention from a statistical point of view. Auto-correlation techniques have been used to reveal hidden periodicities in apparently random waveforms, from which it may be possible to trace and sometimes correct sources of vibration in machine tools. The auto correlation function and more recently the structure function have been successfully used to describe the parameters of irregular waveforms, and to extend this treatment to predict the effect of surface properties on contact conditions and hydrodynamic lubrication.

Cross-correlation has been used to examine the possible modes of engagement of two surfaces resting or sliding on each other, and also as a means of describing topography in three dimensional terms by combining cross-sections taken at different places or in different directions The distribution of ordinates measured from a reference line (or surface), sometimes referred to as the amplitude density, has been thought to be a more sensitive

way of comparing profiles that are somewhat similar in shape than the Abbott-Firestone Bearing Curve although the two procedures have much in common.

3.4.4 Roughness measuring instruments

Surface roughness measuring instruments can be mainly classified into two groups, namely,

a). Stylus instruments and
b). Optical instruments

a) Stylus instruments

The main components of the stylus instruments are:

a) The stylus,
b) The reference datum,
c) The transducer,
d) The amplifier and filter,
e) The recorder or other output such as a meter or computer.

The stylus

The stylus is generally a conical diamond with a spherical tip. ISO 3274 specifies a cone angle of 60° (or 90°) with a tip radius of 2 µm ,5 µm or 10 µm. When a rounded tip is used the theoretical condition for full penetration into the scratches is that the radius of curvature of the bottom of the scratch should be greater than that of the stylus. In practice these distinctions tend to be over-ridden by elastic effects and by the residual roughness of the tip itself.

The nominal value of the static measuring force is specified as 750 µN. The nominal rate of change of the measuring force should be zero.

The reference datum

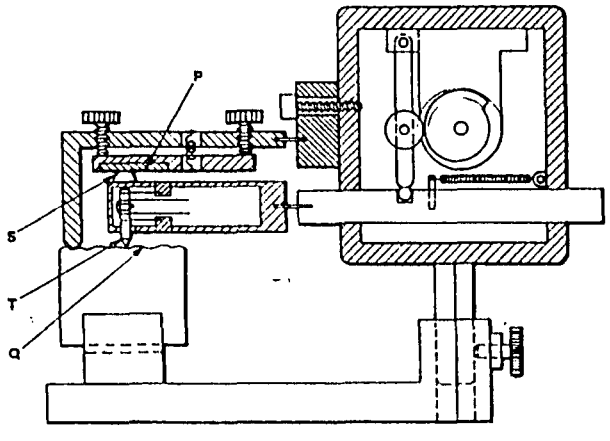


Figure 3.15 –Reference datum of stylus instrument

Several types of reference datums are used depending on the type of surface to be measured. In Figure 3.15, a rounded foot S mounted on the pick-up body immediately above the stylus T rides along an easily renewable optical reference surface p which is positioned over the surface Q to be tested. The slideway or linkage, except for its residual mechanical errors, permits a true cross-section of all undulations to be obtained regardless of their spacing; but the need for accurate leveling and rigidity of the framework has led to widespread use of approximate devices involving a member sliding on the surface to be tested.

In one form shown diagrammatically in Figure 3.16 the pick-up body is hinged to the driving mechanism at H, and provided with a rounded foot S adjacent to the stylus T. The foot rests on the specimen Z and slides across it together with the stylus. Q represents a displacement-sensitive device.

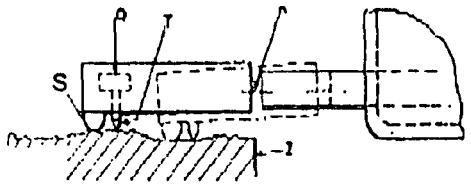


Figure 3.16-Stylus pick up

A pair of rounded feet is often used, as shown in Figure 3.17(a), or a swivelling pad which fits the nominal shape of the surface at least in the direction of motion, as shown in Figure 3.17(b).

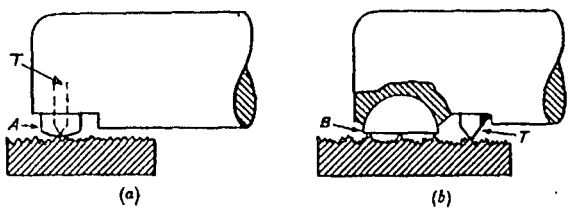


Figure 3.17-Skids and shoes used as reference datum in stylus instruments

The quantity revealed by the instrument is the vertical movement of the stylus relative to the skid or shoe. In the case of the skid, the datum is the locus of the centre of curvature of the skid as it slides over the surface. When the principal crests are close enough together, the vertical movements of the skid will be very small as shown in but as the spacing increases so will the movement of the skid, until finally it moves up and down as much as the stylus. Since the skid and stylus cannot touch the surface at the same point, the combined result will depend on the relative phase of the two movements as well as on their amplitudes. Phase effects will be found no matter where the skid is positioned relative to the stylus, whether in line with it or at the side

If the skid and stylus move up and down together their relative movement can fall substantially to zero, while if their movements are 180° out of phase the height of the resulting graph can rise to twice its proper value. For an intermediate phase the graph may still be nearly correct even though the skid is moving up and down as much as the stylus. When, as so often happens, the spacing is irregular, some undulations may be exaggerated and other undulations diminished in such a way that although the graph is in a sense false it still gives the right impression of the surface. The practical limits of the skid are therefore not calculable and have to be learned from experience.

The bulk of modern instruments use skids from 25 to 50 mm. radius, and are serviceable for most of the finer cut and abraded surfaces, for which the characteristic spacing is generally less than 0.75 mm. Unfortunately such instruments are also used all too often for measuring the rougher surfaces produced by milling, scraping, and planing, or those afflicted with widely spaced chatter marks, for which surfaces the resulting representation may be very misleading.

The difficulties resulting from the curvature of the skid can often be largely avoided by means of the shoe shown in Figure. 3.X(b). Provided the crests are reasonably uniform in level, and are spaced apart by not more than half the length of the shoe, a very serviceable datum will be provided. The shoe tends to be more costly and bulky than the skid, and to need more careful alignment in holes.

Curyed surfaces can often be tracked by approximating to them an easily generated curve such as the arc of a circle. This has been accomplished with sufficient accuracy by a pivoted

link of appropriate length. The lay of the roughness to be measured must of course be such that the stylus crosses the scratch marks and does not follow their length.

The transducer

The transducers are of two basic types :

1. Carrier modulating devices, in which the amplitude of an alternating current of high frequency (carrier)is controlled in real time(modulated) according to the position of the stylus relative to the datum, and
2. Current or voltage generating devices, in which a current or voltage is generated according to the motion of the stylus as it is displaced from one level to another.

The amplifier

The amplifiers are of two basic types;

a) Carrier modulating devices, in which the amplitude of an alternating current of high frequency (the carrier) is controlled (modulated) at every instant of time according to the position of the stylus relative to the datum.

b) Current or potential generating devices, in which a current or voltage is generated according to the motion of the stylus as it is displaced from one level to another, provided the up and down movements follow each other quickly enough.

Carrier modulating instruments are ideal for obtaining profile graphs .because they can faithfully reproduce every movement of the stylus relative to the datum regardless of the spacing of the peaks.

The filter

Electrical filtering is used exclusively in modern instruments. An alternating current representing the profile is passed through an electric wave filter. A filter which has been standardised comprises of two capacitor resistor networks of equal time constant connected in cascade as shown in Figure 3.18. Such a filter is known as a 2-CR filter.

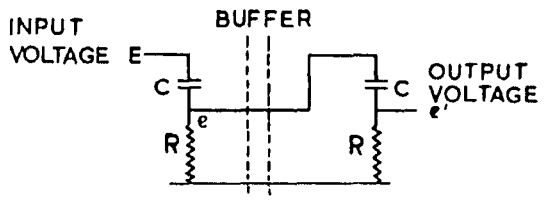


Figure 3.18-Simple 2-CR filter circuit

It is found that if the long wavelength cut-off of the filter is made equal to the sampling length of the graphical process (Figure 3.12), the degree of filtering given by the graphical and electrical methods is similar ,and that although results are often not identical they are sufficiently close for practical purposes.

However the problem of the simple 2-CR filter is that it introduces a phase shift between the input and out put signals. The phase shift causes distortion of the waveforms of frequencies lying just inside of the long wavelength cutoff. Due to this reason it is now more common to find instruments fitted with phase correct filters conforming to the requirements of ISO 11562 :1996.

b) Optical instruments

Optical instruments are mainly of three categories, those using interferometry, laser profilometry and optical scattering.

The interference method

The optical principle is shown in Figure 3.19(a).Z is the surface to be tested.O an optical test plate.A beam of collimated monochromatic light of which p,q are rays is reflected by the flat under-surface of the test plate and partly by the surface of the specimen. After reflection the beams re-combine; but because of the separation of the surfaces, the beam from the test surface.reflected from the specimen will lag in time, and hence in phase.

If the specimen Z is not flat, or is inclined to the test plate, the intersection of each critical plane with the surface under test will trace a contour line which will be either bright or dark. Suitably viewed, and selecting one or the other, the eye will therefore see a simple contour map of the surface, and these contours will be separated by half the wavelength of the light used, that is by approximately 0.25 μm for green light. The effect will be most marked when the two beams contribute equal energy to the interference pattern, a condition which can often be secured by partially metallizing the undersurface of the test plate.

For examining the general shape of the surface, the simple arrangement shown in Fig. 3.19(b) can be used. For viewing the scratch marks some degree of magnification is required and a microscope is focused on the surface. One arrangement suitable for low powers is shown in Figure 3.19(c). The reference plate O is then very slightly inclined to the surface, with the line of intersection approximately at right angles to the direction of the scratch marks. The resulting interference fringes trace oblique Sections of the texture. The separation of successive fringes again represents a depth of half a wavelength, assuming that the normal cross-section of the scratches remains constant from one fringe to the next.

A micro-interferometer permitting the use of high aperture objectives (N.A. 0.58) has been derived from the Michelson interferometer by Linnik. The principle is shown in Figure 3.19(d). Very high resolving power approaching. 0.5 μm spacing of the scratch marks can be secured. A method of reducing the width and increasing the sharpness of the fringes by permitting multiple reflections to occur between the specimen and the reference surface has been highly developed by Tolansky and instruments incorporating the principle can now be obtained.

The reference surface has to be placed close to the specimen, so that the basic form shown in Figure 3.19(c) has to be employed, unfortunately with the restrictions on aperture and resolving power that this construction involves. Both surfaces have to be highly reflective, which is generally ensured by metallizing.

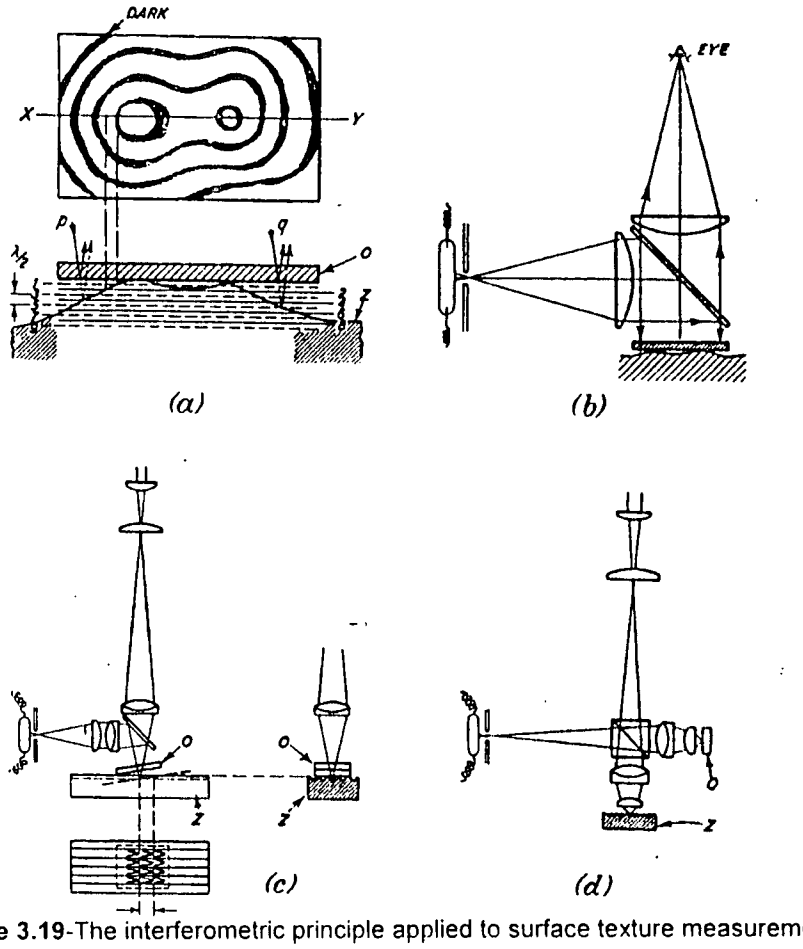


Figure 3.19-The interferometric principle applied to surface texture measurement

Laser profilometer

A laser beam produced by a solid-state laser head is directed on to the surface under test while the surface is moved through a small distance. The focusing lens of the laser head is mounted on a leaf spring arranged inductive coil system by which transient out-of-focus is corrected by movement of the focusing lens. Figure 3.20 shows a schematic of the principle of maintaining focus. The laser beam size is about 1 mm and focus is maintained by feedback via photo sensors, which compare the projected light to the reflected light through a beam splitter. Focus position is maintained by inductively moving the focusing lens to maintain a balance of position of the projected and reflected beams.

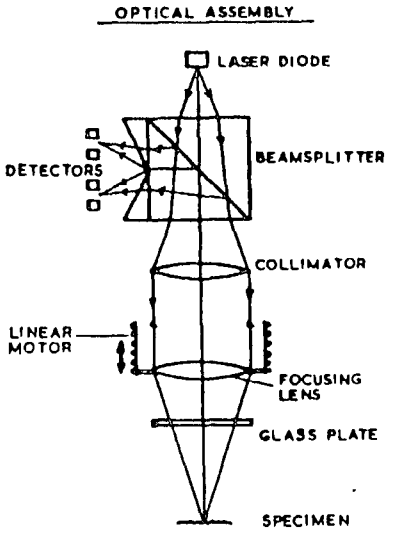


Figure 3.20-Optical arrangement of a laser profilometer

The feed back signal from the photos-sensors represents the motion of the focusing lens, and hence, in principle, represents the profile encountered to maintain focus. A block diagram of the system and the associated electronics to achieve a linear signal output from such a device is shown in Figure 3.21.

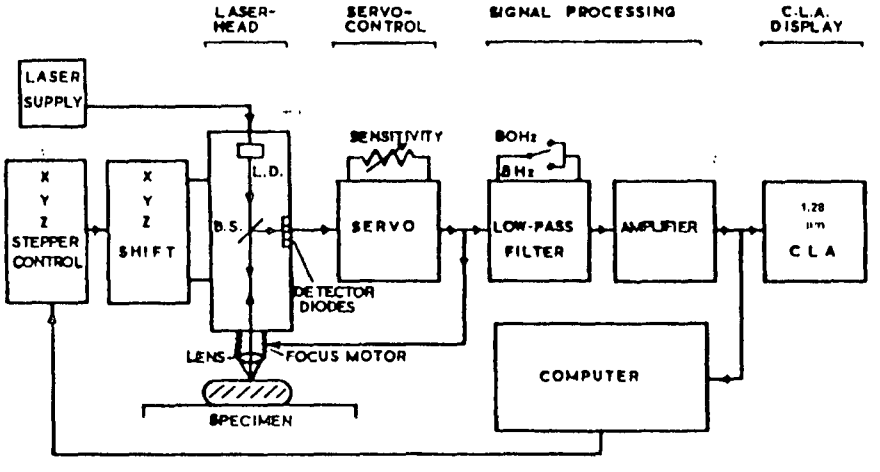


Figure 3.21 –Schematic of the electronics of the laser profilometer.

Optical diffusion and scattering method

In the Optical Diffusion methods, a beam of light, generally in the form of a narrow pencil, is directed onto the surface either normally or at some assigned angle, and the extent to which the light is scattered by the surface roughness is measured. Some instruments are based on comparing the amount of light emitted in the specular direction (i.e. the direction determined by a polished surface) with the amount diffused either in all directions or at some chosen angle to the specular direction, photo-electric detectors being used. Other instruments (often described as gloss meters) measure the diffused light only; but the results may then be affected by the brightness or darkness of the surface (e.g. by tarnish) apart from the roughness.

A recent approach is to scan the diffused light with a slit in a rotating shutter, and obtain a measure from the rate of change of the output. The relation between optical diffusion and surface topography is rather complex. It involves amplitude, slope, and spacing; it depends

on the degree of randomness or periodicity; and it is affected by the dimensions of the topography compared with the wavelength of light.

c) Other instruments

Area methods

Measurement of surface texture over a selected area, instead of along a selected cross-section, is obviously attractive, and many attempts have been made to measure surfaces on this basis. Pneumatic instruments are based on measuring the leakage between the surface and a nozzle held in proximity to it, the leakage increasing with the roughness

In the case of Capacitance instruments, a condenser plate is positioned over the surface by a spacing device (sometimes a film of dielectric material). Increasing roughness causes the average gap to increase and hence the capacitance to fall, from which a measure of the roughness is obtained. The pneumatic and capacitance methods set problems when the surface to be tested is other than flat, for even if the nozzle or condenser plate is curved to fit the nominal shape of the surface, the effects of dimensional limits can sometimes over-ride those of the roughness.

Scanning electron microscopy

The new generation of instruments include the scanning microscopes such as the Scanning Electron Microscope (SEM), the Scanning,Tunnelling Microscope (STM) and the Atomic Force Microscope (AFM).

4 Mass measurements

4.1 Introduction

The concepts of mass measurement are outlined in this chapter. The calibration of weights and balances is described in Chapter 11.

4.2 Primary standard

The international prototype kilogram made from platinum iridium alloy and maintained at the Bureau des Poids et Mesure (BIPM) in Sevres, France is the primary standard for mass measurements. The kilogram remains to be the only artifact standard of the SI system of units (Figure 4.1).

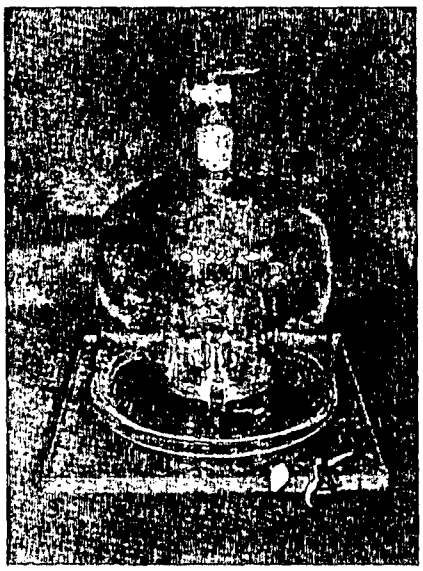


Figure 4.1 International prototype kilogram (Source :BIPM).

4.3 Secondary and working standards

At the signing of the Treaty of the Metre, 48 copies of the kilogram were made and distributed to the 48 national laboratories of the member countries. These kilograms constitute the secondary standards of mass. Countries, which joined the metre convention later, were also given a copy of the kilogram.

In addition national laboratories maintain a set of weights known as tertiary(working) standards. These standards are used for calibration of weights used in industry and trade & commerce, except in those circumstances where uncertainty of the weights requiring calibration demands a higher level standard to be used.

4.4 Mass & weight

Mass and weight are often confused as synonymous, though they are two distinctly different quantities. Mass is defined as the amount of matter in an object. It is also defined using Newton's second law of motion, namely,

$$F = m \times a \qquad (4.1)$$

(Force) = (mass) x (acceleration)

Each object possesses a property called "mass" which appears in the equation as the constant of proportionality between a force (F) applied to the object of mass (m) and the resulting acceleration (a) of the object.

The weight of an object is the force experienced by it due to the earth's gravity. Since an object of mass (m) will accelerate through "g", the acceleration due to gravity, we can write the above equation for motion under gravity:

$$W = m \times g \qquad (4.2)$$

W is known as the weight of the object. Thus, the weight of an object would vary by a very small amount, as it moved about from place to place, on the surface of the earth, due to the variation of the value of 'g'

Weight being a force should be measured in force units, in SI, the unit is the Newton (N). In the older metric systems of units, namely the centimeter-gram-second (CGS) and metre-kilogram-second (MKS) systems, the units 'gram-weight' and the 'kilogram-weight' were used. However a problem arose due to these units, defined as the force exerted by earth's gravity on a mass of one gram or one kilogram respectively, being dependant on the value of "g", the gravitational acceleration. To overcome these difficulties, a unit for measurement of force known as the 'kilogram-force' was defined. The kilogram-force is the force experienced by a kilogram due to a standard acceleration of 9.80655 m/s^2.

In coherent SI units, these difficulties do not arise, as mass and force are measured using distinctly recognizable non-gravitational units, namely the kilogram and the Newton. The Newton is a derived unit of the SI defined, as the force required accelerating a mass of one kilogram through 1 m/s^2

4.4.1 Mass standards - types and classes

a) Types of masses

Masses are classified in to categories depending upon their material and type of construction. The four main types are :

1. Integral masses made from a non-magnetic stainless steel,
2. Non-integral or two piece masses made from non-magnetic stainless steel. The mass value can be adjusted by the addition or removal of material from a small compartment usually underneath the screw knob.
3. Masses made from brass (plated or unplated, Integral or non-integral) and
4. Cast - Iron masses, usually painted.

Masses of types 1 and 2 are used as reference standards for calibrating masses of lower accuracy classes and testing precision balances. For the verification of normal industrial and commercial weighing equipment masses of types 3 and 4 may be used.

b) Classes of mass standards

The classification of Mass Standards into different classes is based on the maximum deviation of the 'Conventional value' of the mass from its 'Nominal value'. The OIML, classification system is now widely used. The basic features of this system are given below:

c) OIML RI-111 Classification

Maximum permissible error

There are seven classes defined in the OIML RI-111:1994Recommendation (under revision), namely classes E1, E2, FI, F2, M1, M2 and M3. The exact requirements of the different classes are defined in the document. The maximum permissible errors are indicated in Table 4.1 and Table 4.2. Maximum permissible errors of weights conforming to OIML International Recommendation RI-111 and used for testing of high capacity weighing machines are given in Table 4.2.

Table 4.1- Maximum Permissible Errors of OIML R111 masses (Source : OIML)

Nominal Value	Maximum permissible deviation in mg (±)						
	Class E_1	Class E_2	Class F_1	Class F_2	Class M_1	Class M_2	Class M_3
5000 kg	-	-	25 000	85 000	250 000	850 000	1 250 000
2000 kg	-	-	10 000	33 000	100 000	330 000	1 000 000
1000 kg	-	1 600	5 000	16 000	50 000	160 000	500 000
500 kg	-	800	2 500	8 000	25 000	80 000	250 000
200 kg	-	300	1 000	3 000	10 000	30 000	100 000
100 kg	-	160	500	1 600	5 000	16 000	50 000
50 kg	25	80	250	800	2500	8000	25000
20 kg	10	30	100	300	1000	3000	10000
10 kg	5	16	50	160	500	1600	5000
5 kg	2.500	8	25	80	250	800	2500
2 kg	1.000	3	10	30	100	300	1000
1 kg	0.500	1.600	5	16	50	160	500
500 g	0.250	0.800	2.500	8	25	80	250
200 g	0.100	0.300	1.000	3	10	30	100
100 g	0.050	0.160	0.500	1.600	5	16	50
50 g	0.030	0.100	0.300	1.000	3	10	30
20 g	0.025	0.080	0.250	0.800	2.500	8	25
10 g	0.020	0.060	0.200	0.600	2.000	6	20
5 g	0.016	0.050	0.160	0.500	1.600	5	16
2 g	0.012	0.040	0.120	0.400	1.200	4	12
1 g	0.010	0.030	0.100	0.300	1.000	3	10
500 mg	0.008	0.025	0.080	0.250	0.800	2.500	-
200 mg	0.006	0.020	0.060	0.200	0.600	2.000	-
100 mg	0.005	0.016	0.050	0.160	0.500	1.600	-
50 mg	0.004	0.012	0.040	0.120	0.400	-	-
20 mg	0.003	0.010	0.030	0.100	0.300	-	-
10 mg	0.003	0.008	0.025	0.080	0.250	-	-
5 mg	0.003	0.006	0.020	0.060	0.200	-	-
2 mg	0.003	0.006	0.020	0.060	0.200	-	-
1 mg	0.003	0.006	0.020	0.060	0.200	-	-

Conventional mass

The conventional mass value (m_c) of each weight should not differ from the nominal mass value of the weight(m_o), by more than the difference of the maximum permissible error, δm, and the expanded uncertainty($U_{k=2}$) :

$$m_o - (\delta m - U) \leq m_c \leq m_o + (\delta m - U) \qquad (4.3)$$

Expanded Uncertainty

The expanded uncertainty, of the conventional mass U (k=2), of each weight should be less than or equal to one third of the maximum permissible error given in table 4.1 and Table 4.2.

$$U_{k-2} \leq \frac{\delta m}{3} \qquad (4.4)$$

Material

The weights are made from a metal or metal-alloy. Generally Platinum- Iridium (class E1), stainless-steel (classes E2, F1, and F2), brass or plated bronze (classes F2 and M1), cast iron (classes M2 and M3) are used. The metal or alloy of class E1, E2 and F1 weights must be practically non-magnetic

The metal or the alloy of which class M1 rectangular bar weights from 5 kg to 50 kg are made must be no more susceptible to corrosion and no more brittle than grey cast iron. Class M1 cylindrical weights up to 10 kg must be made of brass or of a material of quality at least equal to that of brass.

Density

The density of the material from which the weights are made should be such that a deviation of 10% from the specified air density (1.2 kg/m3) would not produce an error exceeding 1/4 of the maximum permissible deviation given in Table 4.1.

Table 4.2- Maximum Permissible error for intermediate classes of weights equal to or greater than 50 kg (Source :OIML)

	Maximum permissible error, ±δm in g	
	0.00033 kg/kg	**0.0001 kg/kg**
Scale divisions, n_{max} →	**1000 : Class M_{2-3}**	**5000 : Class M_{1-2}**
Nominal value		
5000 kg	1700	500
2 000 kg	660	200
1 000 kg	330	100
500 kg	170	50
200 kg	66	20
100 kg	33	10
50 kg	17	5

d) Other classifications

In the United States, the classifications of weights in to classes and types are given in three primary publications :

ANSI/ASTM E 617-91 - Standard specification for laboratory weights and Precision Mass Standards and

NIST* Handbook 105-1 (1990) - Specifications and Tolerances for Reference Standards and Field Standard Weights and Measures.

NIST Handbook 44 –Specifications and Tolerances for standard weights.

e) Types and classes of balances

Weighing balances are classified into types by the design and weighing principle used and into classes by metrological criteria. Balances used for laboratory weighing and precise measurements are classified into the following main categories:

a) Two pan, Three Knife-Edge balances

b) Single pan, Two Knife-Edge balances

c) Electromagnetic, Force-compensation balances

A brief description of each type follows:

f) Two-pan, three-knife-edge balances

A schematic of a two-pan, three-knife-edge undamped balance is shown in Fig 4.2.

These balances consist of a main beam carrying two pans at its ends. The beam has a central knife edge resting on a bearing pad when the balance is in operation. The two pans are supported by knife edges at the extremities of the beam. All the three knife edges lie in a plane. The central knife edge is nominally equi-distant from the pan knife edges and due to this reason these balances are also known as equal arm balances. The balance beam is arrested (raised) while not in use and released (lowered) when a weighing is to be carried out. A pointer attached to the beam moving over a scale is used to read the rest point or the turning points of the beam. Presently this type of balance is mostly used in high precision metrology laboratories for calibration of secondary and tertiary level mass standards.

There are two types of equal arm balances, undamped or free swinging balances and damped balances;

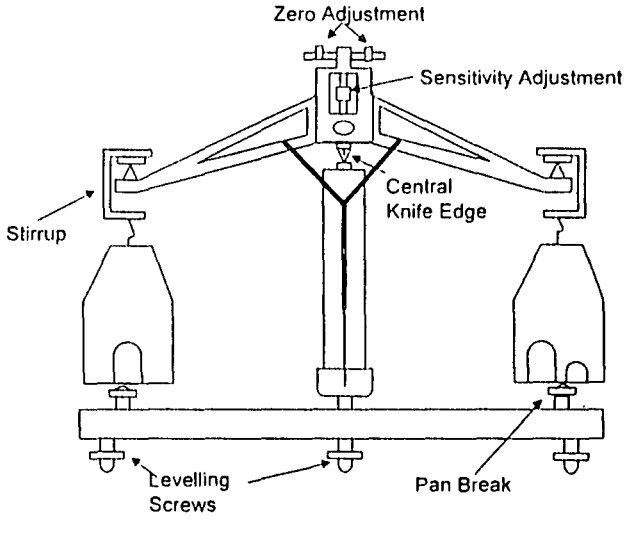


Figure 4.2 -Two pan, three knife edge balance

Undamped or free-swinging balance

Undamped balances are subject to only slight natural damping and come to rest after a long period of time. The rest point of these balances is determined by reading the turning points of the beam in oscillation. There are a number of formulae used to calculate the rest point . A widely used formula to calculate the rest point is,

$$\text{Rest point} = [(t_1+t_3+t_5)/3 + (t_2 + t_4)/2]/2 \qquad (4.5)$$

In the above equation t1,t2,t3,t4 and t5 are the successive values of the turning points. Undamped balances are more sensitive than damped balances though they are not as convenient to use.

Damped balances

Damped balances have an arrangement to provide damping of the beam oscillations using air, oil or a magnetic field as the damping medium. Damping is generally arranged to be critical so that the pointer crosses the rest point once and comes to rest. The rest point of the balance is usually read off an optical scale fixed in front of the balance or in more modern balances an electronic digital display is provided.

g) Single-pan, two-knife-edge balances

Both analytical and top-loading types of balances use this principle. A schematic diagram of an analytical balance is given in Figure 4.3.

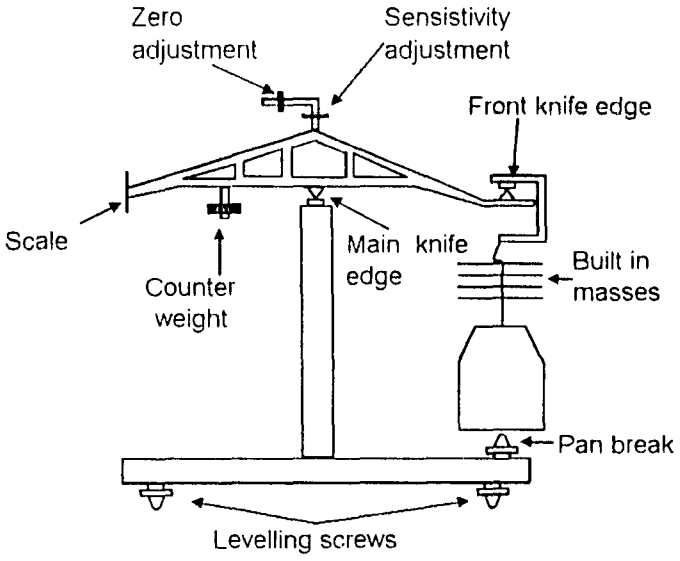


Figure 4.3-Single pan two knife edge analytical balance

In this type of balance the beam carries a single pan at one of its ends. The beam has a knife-edge fixed to it, which rests on a bearing. A counter weight is used to balance the beam when it is released on to the bearing. Two movable masses attached to screw pins are used to adjust the balance sensitivity and rest point. The beam is critically damped using an air dash-pot.

The balance also has built in masses attached to the pan end of the beam. The masses can be lifted off the beam by a dial mechanism fixed to the balance case. Whenever a load, whose mass is to be determined is placed on the pan, an equivalent mass is lifted off the beam by dialing, until the reading comes within the optical scale of the balance. The mass of the load placed is then read as the total sum of the dial readings plus the optical scale reading.

In the analytical type of balance the load is suspended below the balance beam and the beam is arrested during loading and unloading of the pan. For the top-loading balance the pan is supported above the beam by a parallelogram linkage and there is usually no arresting mechanism.

Since the mass to be supported by the knife-edges is fairly constant, this type of balance is also known as a 'constant-load balance'. Also the sensitivity of the balance remains practically constant as the total beam load remains constant at all pan loads. Most older generation analytical balances are of this type.

h) Electromagnetic force-compensation balances

This type of balance works on the principle of electro-magnetic force compensation and the gravitational force exerted on an object to be weighed is directly measured in contrast to

comparison of forces done, in the case of beam type balances. Fig. 4.3 shows a schematic diagram of the balance.

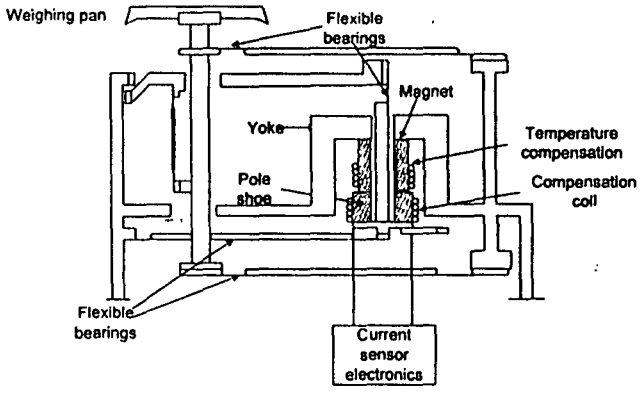


Figure 4.4 Electromagnetic **force compensation balance**

A coil rigidly attached to the pan linkage of the balance is placed in the annular gap of a magnet. When a load is placed on the pan a position sensor detects that the pan has been lowered and causes the current through the coil to be increased, generating a magnetic counter balancing force bringing the balance pan to its original position. The compensating current is converted to a voltage by passing it through a resistor and read out on what is effectively a digital voltmeter.

In most of the modern electronically operated precision balances a microprocessor is incorporated in the circuitry. The level of sophistication of these instruments is very high, and there are many balance functions and features, which have to be learnt by a careful reading of the operation manual. Let us examine the electronic capabilities that are inherent to the basic balance and those that may be optional.

All balances have a digital display to indicate "mass". Additional features include taring control, dual capacity and precision, selectable sampling period, in-built calibration mass etc. A brief summary of these features follows:

Taring control

The taring control is a facility to zero the balance display when a load is placed on the pan. This facility permits one to subtract the mass of an object (such as a weighing boat or a watch glass) which is common to a series of weighings.

Dual capacity and precision

A feature which allows the balance capacity to be varied by a predetermined amount with a comparable change in precision.

Variable sampling period

Sampling period is the time interval used for averaging the sensing parameter. Provision is made so that this interval can be varied.. As the sampling interval is lengthened the overall balance weighing cycle is likewise lengthened.

Filters

Electronic filters that eliminate certain portions of the noise spectrum from the servo loop are provided.

Computer compatibility

Facilities to interface the balance output to an external computer using BCD, RS-232C or IEEE-488 interface protocols are provided.

Computation

A balance option that does computations such as counting, standard deviation calculations or user-defined computations. .

Elimination of poor data

A facility to protect the user from collecting poor data, due to unusually strong air currents or vibrations, by not displaying the weighing results during these periods. Usually an override capability to cancel the protecting mechanism is provided.

Although the electromagnetic force compensation balances are widely used today, there are some occasions where the use of these balances may give rise to problems.

Weighing Ferromagnetic material

The magnetic field associated with the servomotor may be changed by the presence of ferromagnetic materials giving rise to systematic errors in the indication of the balance. This can be verified by moving the material in and around the balance pan while observing the zero reading. The effect may be minimized by weighing below the balance pan if this is possible.

Electromagnetic radiation

The presence of a strong electromagnetic field may give rise to variable readings or malfunctioning.

Dust Susceptibility

These balances are very sensitive to dust in the environment. When dust particles enter the gap between the permanent magnet and the pole pieces of the servomotor the precision and calibration of the balance can change. If the particles are ferromagnetic the balance may be rendered inoperable. Such environments should be avoided.

4.4.2 Mass comparators

Mass comparators are used for comparison of precise masses. Generally the construction of these balances is similar to electromagnetic force compensation type but they are built with more precision and stability. Mass comparators are available in capacities in the range 2 g to 20 kg with excellent repeatability and linearity.

4.4.3 Industrial weighing systems

There is a large variety of equipment used for carrying out weighing operations in industrial situations. These systems use a variety of weighing principles. They are also classified as mechanical, electrical, hydraulic or pneumatic types .The most common types of weighing systems are operated mechanically or electrically.

4.4.4 Mechanical systems

Most mechanical weighers use knife edge and lever systems. Some mechanical balances use pendulum systems to carry out the weighing operation. Mechanical systems often require no electrical power. Usually these are mass comparison devices independent of gravity and have very good accuracy. However the maintenance requirement of these systems are high. Also they are not suitable for use in environments where deposits may form on the knife edges. Two examples of mechanical balances are given below:

4.4.5 Electrical systems

Electrical weighing systems largely consist of load cells connected either in series or parallel configuration. A load cell generates an electrical voltage output in proportion to the load applied on a fixed metallic member. Resistance strain gauges, capacitance, force balance and resonant wire cells are used as the load-sensing element in load cells.

There are many advantages of electrically operated systems. Electrical output is suitable for remote transmission and for interfacing with computers and modern instrumentation used in

process control. A wide range of capacities (milligrams to thousands of tonnes) with high speed and accuracy are available. These systems are also suitable for both static & dynamic weighing, as well as weighing in hazardous areas provided special precautions are taken.

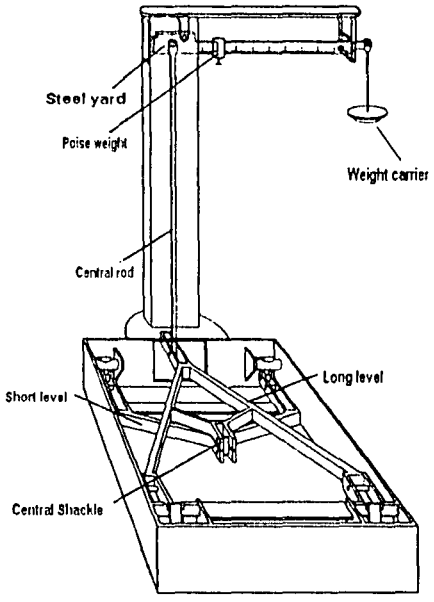


Figure 4. 5-Platform scale

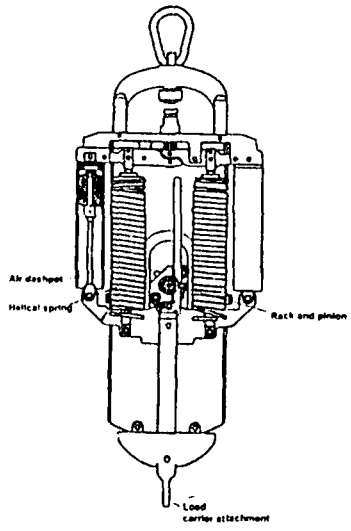


Figure 4.6-Helical spring scale

4.4.6 Pneumatic systems

In some industrial situations a pneumatically operated weighing system is used. A pneumatic weighing system is a force balance system, which uses air to transmit the force generated in a lever system. Usually compressed air is used as the force transmission medium.

Pneumatic systems require no electrical power and are Intrinsically safe in hazardous environments. They can also be used for remote indication and are often fitted with self-indicating analogue dials. Accuracy of these systems is generally good.

On the debit side the maintenance level of these systems is high. They also need a clean compressed air supply

4.4.7 Hydraulic systems

Hydraulic systems use fluids to transmit the force generated by the mass via a piston acting in a cylinder. These cylinders usually take the form of a load cell. Hydraulic systems require no electrical power supply. Tensile versions are available for suspended load. Generally maintenance level is high and fluid leakage is a problem. Also multiple cells and special hydraulic force summing devices are required for supported load. Hydraulic systems measure force and are therefore sensitive to gravitational variations. Accuracy of these systems is limited.

4.4.8 Accuracy classes of balances

A classification of weighing instruments in terms their accuracy classes is given in OIML International recommendation R76-1 for Non–Automatic weighing instruments. Non automatic weighing instruments are classified into four accuracy classes, Special I ,High II ,Medium III, and Ordinary IIII. The classification is based on the verification scale interval (e) and the number of verification scale intervals (n).

a) Actual scale interval (d)

The actual scale interval (d) of a weighing instrument is the value expressed in units of mass of the difference between the values of two consecutive scale marks of an analogue

instrument. In the case of an instrument with a digital display, it is the difference between two consecutive display readings.

b) Verification scale interval (e)

The verification scale interval is used for the classification and verification of a weighing instrument. In an instrument without an auxiliary indicating device, the verification scale interval is equal to the actual scale interval i.e. e=d. For instruments with an auxiliary indicating device or non-graduated instruments the verification scale interval is determined in accordance with the requirements of Table 4.3.

Table 4.3 –Accuracy classes of non automatic weighing instruments (Source : OIML)

Accuracy Class	Verification scale interval, e	Number of verification scale intervals		Minimum capacity min (lower limit)
		Min	Max	
Special I	0.001 g ≤ e	50000	-	100 e
High II	0.001 g ≤ e ≤ 0.05g	100	100000	20e
	0.1 g ≤ e	5000	100000	50e
Medium III	0.1 g ≤ e ≤ 2 g	100	10000	20 e
	5 g ≤ e	500	10000	20 e
Ordinary IIII	5 g ≤ e	100	1000	10 e

5 Pressure measurements

5.1 Introduction

The concepts of pressure measurement are outlined in this chapter. The calibration of pressure measurement standards and test instruments is described in Chapter 12.

5.2 Absolute, gauge and differential pressure modes

If a vessel were to contain no molecules within it, the pressure would be zero. Pressures measured on the scale with zero pressure as the reference point are said to be absolute pressures.

The earth's atmosphere exerts a pressure on all objects on it. This pressure is known as the atmospheric pressure and is approximately equal to 100 kPa. Pressures measured in reference to the atmospheric pressure are known as gauge pressures. The difference between a pressure higher than atmospheric and atmospheric pressure is a positive gauge pressure while the difference between atmospheric pressure and a pressure lower than atmospheric is referred to as negative gauge pressure or vacuum. Gauge pressure values being dependant on atmospheric pressure change slightly as the ambient pressure changes.

The relationship between absolute and gauge pressure is given below :

Absolute pressure = gauge pressure + atmospheric pressure (5.1)

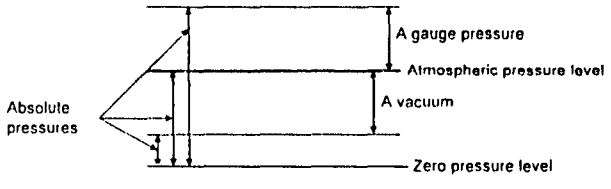


Figure 5.1-Pressure modes and their relationships:

A differential pressure is the difference of pressure values at two distinct points in a system. For example, the flow of a fluid across a restriction in a pipe causes a pressure differential and this is used to determine the flow of the gas or liquid. This is the principle of the orifice plate as shown in Figure 5.2.

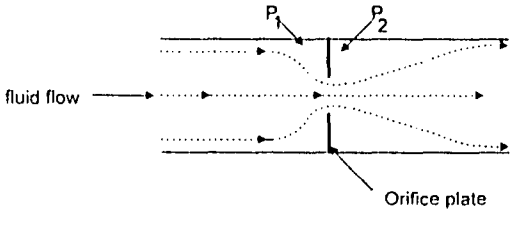


Figure 5.2-Differential pressure in an orifice plate

5.3 Primary standards

A number of different physical standards are used for the realisation of pressure values at the primary level. The two most common instruments for the positive gauge pressure range are the mercury manometer and dead weight pressure tester The spinning ball gauge standard is used in the negative gauge pressure (vacuum) range.

5.3.1 Mercury manometer

The basic principle of the mercury manometer is illustrated in Figure 5.3. Vessels A and B are connected using a flexible tube. Vessel A is at a fixed level while vessel B can be moved up and down using a lead screw mechanism. The output pressure is obtained from vessel A.

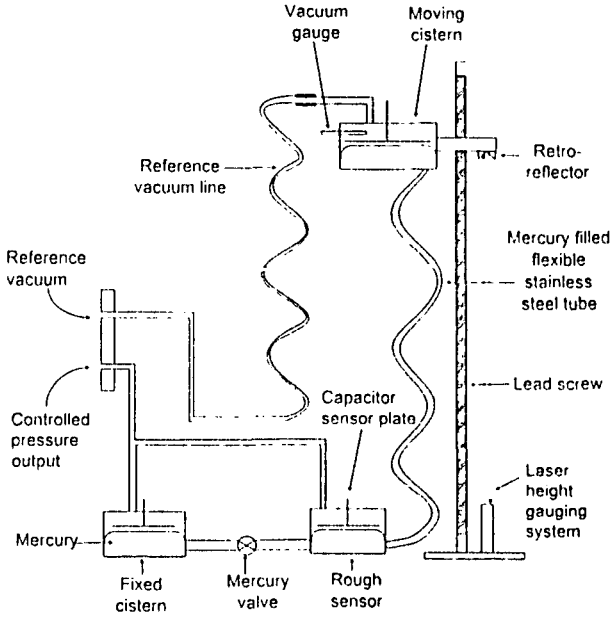


Figure 5.3-Schematic of a typical mercury **manometer**

A vacuum pump is sometimes used to evacuate the air above the meniscus of the moving vessel. Under these conditions the output pressure P_{out} is given by :

$$P_{out} = P_{in} + h.\rho.g \qquad (5.2)$$

Where

Pin - the pressure due to the gas above the meniscus of the moving vessel

h - the difference of height between the mercury levels of the two vessels,

ρ - the density of mercury,

g - local acceleration due to gravity

In some designs, large diameter tubes (several tens of millimeters) are used to reduce capillary depression of the meniscus and other surface tension effects. With these measures uncertainties in pressure of a few parts per million can be achieved. However the mercury temperature (typically to 0.005 °C), the mercury density, the vertical distance between the mercury levels and the local value of gravitational acceleration have to be determined with low uncertainties. Individually built large-bore mercury manometers, using a variety of optical, capacitive, ultrasonic or inductive methods for detecting the mercury surface positions, are used in many national laboratories as primary standards. Slightly less capable instruments are available commercially and measure pressures up to about 3×10^5 Pa.

5.3.2 Dead weight pressure tester

A dead weight pressure tester consists of three main elements, namely the pressure balance, set of dead weights and the pressure source. A schematic of a dead weight pressure tester in its simplest form is shown in Figure 5.4.

The pressure balance consists of a piston inserted into a closely fitting cylinder. The set of weights is usually made from non-magnetic stainless steel in the form of disks stackable on top of each other. Hydraulic pressure generated by a manual or electrically driven pump or

pneumatic pressure obtained from a pressurized vessel is applied to the piston -cylinder assembly of the pressure balance.

Pressure testers used as primary level standards are calibrated by absolute methods by estimating the effective diameter and deformation characteristics of the piston cylinder assembly together with the determination of the mass values of the weights. (see the simple theory of the pressure balance). Dead weight pressure testers are used in the range 3 kPa (gas media, absolute or gauge mode) upto 1 GPa (hydraulic, gauge mode). Uncertainties of the order of ± 0.001 percent of the reading are attainable with these instruments.

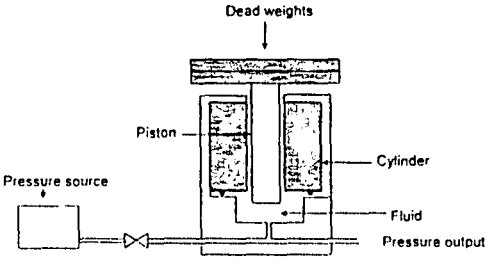


Figure 5.4-Dead weight pressure tester

5.4 Spinning ball gauge standard

A spinning ball gauge standard uses the principle of molecular drag to estimate the molecular density of a gas from which the pressure can be calculated. These standards can only be used for measurement of low absolute pressures below 10 kPa. The principle of the spinning ball gauge standard is illustrated in Figure 5.5.

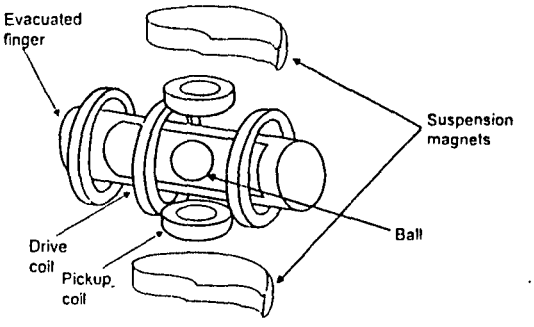


Figure 5.5-Spinning ball gauge standard

A ball made of magnetic steel few millimeters in diameter is housed in a non magnetic tube connected horizontally to a vacuum chamber. The ball is magnetically levitated and spun to few hundred revolutions per second using a rotating magnetic field. The driving field is then turned off and the relative deceleration of the ball is measured with magnetic sensors. The deceleration of the ball due to molecular drag is related through kinetic theory to molecular density and pressure of the gas. The lowest pressure that can be measured is limited by the residual drag caused by induced eddy currents.

An inert gas, usually dry nitrogen is used as the pressure medium. The temperature of the tube is measured accurately using a calibrated thermocouple or other instrument. The spinning rotor gauge is used in the absolute pressure range 10–5 Pa to 10 Pa.

5.5 Secondary standards

The Mercury manometer, dead weight tester and capacitance standard are the most commonly available secondary standards. A brief description of the capacitance pressure standard is given here as the other two standards, namely the mercury manometer and the dead weight tester are covered in other sections.

5.5.1 Capacitance pressure standard

A schematic diagram of a capacitance pressure standard is shown in Figure 5.6. Capacitance standards basically consist of a parallel plate capacitor whose plates are separated by a metallised diaphragm. The diaphragm and the two electrodes form two capacitors which are incorporated in an AC bridge circuit. The deflection of the diaphragm when a pressure is applied to one of the chambers is detected as a change in the capacitances. The two pressure chambers are electrically isolated and the dielectric properties are maintained constant. .

The symmetrical design provides a more or less linear relationship between pressure and electrical output and differential pressures can be easily measured. To measure absolute pressures the reference chamber is evacuated.

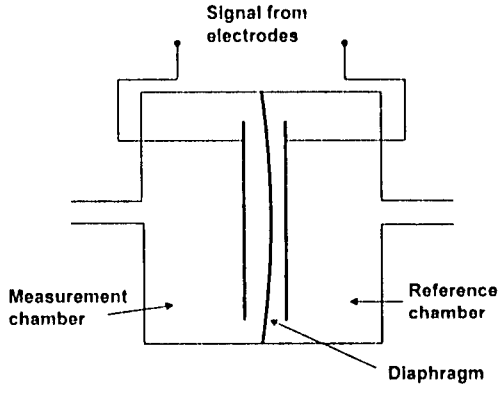


Figure 5.6 Capacitance pressure standard

Capacitance pressure standards operate in the pressure range 10^{-3} Pa to 10^{7} Pa and generally have good repeatability, linearity and resolution. Also they have high over pressure capability.

5.5.2 Quartz crystal pressure standard

Pressure standards employing quartz crystal resonator technology have been in use for the past 20 years.The resonant quartz crystal pressure standards have resolutions better than one microbar (<0.1 Pa) and a repeatability of better than 0.01% of reading (<0.1 hPa) maintained even under difficult environmental conditions.

The remarkable performance is achieved through the use of a precision quartz crystal resonator(Figure 5.7) whose frequency of oscillation varies with pressure induced stress. Quartz crystals are chosen for the sensing elements because of their remarkable repeatability, low hysteresis, and excellent stability. The resonant frequency outputs are maintained and detected with oscillator electronics similar to those used in precision clocks and counters.

Several flexurally-vibrating, single or dual beam, load-sensitive resonators have been developed. The Double-Ended Tuning Fork consists of two identical beams driven piezoelectrically in 180° phase opposition such that very little energy is transmitted to the mounting pads. The high Q resonant frequency, like that of a violin string, is a function of the applied load; increasing with tension and decreasing with compressive forces. The digital temperature sensor consists of piezoelectrically-driven, torsionally oscillating lines whose

resonant frequency is a function of temperature. Its output is used to thermally compensate the calculated pressure and achieve high accuracy over a wide range of temperatures.

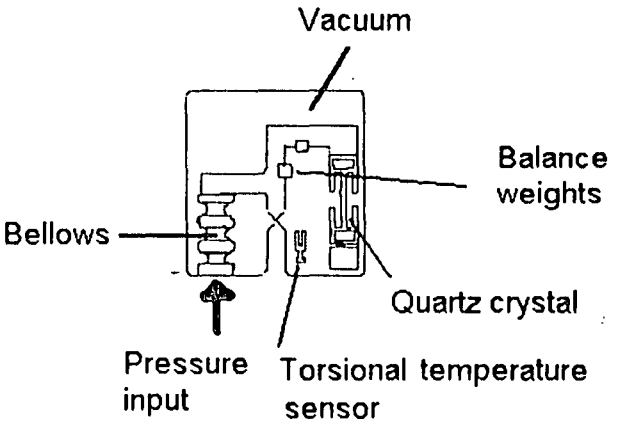


Figure 5.7-Quartz crystal pressure transducer

The barometer mechanisms employ bellows as the pressure-to-load generators. Pressure acts on the effective area of the bellows to generate a force and torque about the pivot and compressively stress the resonator. The change in frequency of the quartz crystal oscillator is a measure of the applied pressure. Temperature sensitive crystals are used for thermal compensation. The mechanisms are acceleration compensated with balance weights to reduce the effects of shock and vibration. The transducers are hermetically sealed and evacuated to eliminate air damping and maximize the Q of the resonators. The internal vacuum also serves as an excellent reference for the absolute pressure transducer configurations. Since any changes in the reference vacuum directly affect the pressure output, great care is taken to ensure that there are no leaks and minimal outgassing in the evacuated housing.

5.6 Working standards

The most commonly used working standard is the dead weight pressure tester. A number of other instruments, such as precision bourdon or diaphragm type dial gauges, strain gauges, piezo resistive pressure sensors and liquid manometers are also used as working standards.

5.1.1. Dead weight pressure tester

a) The pressure balance

The most critical element of a dead weight pressure tester is the pressure balance. Pressure balances normally encountered are of two kinds, hydraulic (uses oil as the pressure medium) and pneumatic (uses air or nitrogen as the pressure medium). The latter type often has a facility to evacuate the ambient space around the piston-cylinder assembly, thus permitting their use for *absolute* as well as *gauge pressure* measurements.

The simple, re-entrant and the controlled clearance types shown in Fig. 5.7 are the three basic types of pressure balances in common use today. Although there are a number of technical and operational differences, the general principle of pressure measurement for the three types is the same.

b) Simple type

The geometry illustrated schematically in Figure 5.8 (a) is that of the simple type, where the piston and cylinder have basic cylindrical shapes. The calculation of the elastic deformation of this design is straight forward. Because fewer variables are needed to predict the deformation, the pressure coefficients can be estimated with a relatively small uncertainty. This design is commonly used for pressures up to 500 MPa and sometimes with appropriate modifications up to 800 MPa. At higher pressures distortion of the piston and cylinder

becomes significant and the annular gap between the piston and cylinder is so large that the gauge does not operate well.

c) Re-entrant type

In the re-entrant type, illustrated schematically in Figure 5.8 (b), the pressure transmitting fluid acts not only on the base of the piston and along the engagement length of the piston and cylinder but also on the external surface of the cylinder. This external pressure reduces the gap between the piston and the cylinder thus reducing fluid leakage. The upper pressure limit is set by the reduction of the gap to an interference fit.

The disadvantage of this design is that it is difficult to accurately estimate the effects of distortion on the effective area of the piston and cylinder.

d) Controlled clearance type

In the controlled clearance type, illustrated schematically in Figure 5.8 (c) , an external pressure is applied to the exterior surface of the cylinders enabling control of the gap between the piston and the cylinder. Using this design, in principle a very wide range of pressures can be covered using only one piston cylinder assembly. However in practice a series of assemblies is used to achieve the best sensitivity for a particular pressure range. This type of pressure balance is most commonly used in very high-pressure applications.

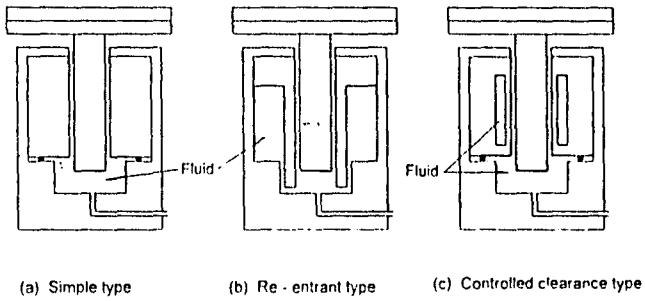


Figure 5.8 Types of pressure balance

e) Simple theory of the pressure balance

The simple theory of the pressure balance is based on the application of laws of hydrodynamics or aerodynamics depending on whether the pressure transmitting medium is a liquid or a gas. The simple theory is explained using Figure 5.9.

The piston and cylinder are assumed to have straight and smooth cylindrical surfaces of circular cross section of radii r and R respectively. The fluid pressure being measured, P_1 is applied to the base of the piston while the top of the piston is exposed to ambient pressure, P_2. At the equilibrium condition the upward vertical force arising from the pressure difference P_1-P_2 is balanced against a known downward gravitational force, W, which is applied to the piston by means of calibrated masses.

When the piston is in equilibrium,

$$W = \pi r^2 (P_1 - P_2) + F \qquad (5.3)$$

Where F represents a frictional force exerted on the vertical flanks of the piston by the fluid that is being forced to flow upwards under the influence of the pressure gradient.

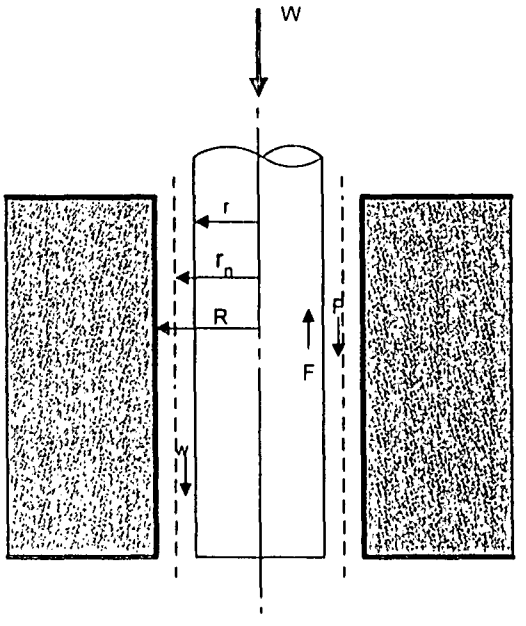


Figure 5.9-Diagrammatic representation of the pressure balance piston-cylinder assembly (with clearances greatly exaggerated).

The vertical component of the fluid velocity is at a maximum approximately halfway between the bounding surfaces (piston and cylinder surfaces) and it is zero at the bounding surfaces. The cylindrical surface at which the fluid velocity is maximum and frictional forces between adjacent layers are minimum is called the *neutral surface.* By equating the forces acting on the column of fluid of annular cross-section contained between the surface of the piston and the neutral surface, and denoting the downward force due to its weight as w the following equation is obtained :

$$w + F = \pi(r_n^2 - r^2)(P_1 - P_2) \qquad (5.4)$$

Combining equations 5.3 and 5.4 gives :

$$P_1 - P_2 = \frac{w + W}{\pi r_n^2} \qquad (5.5)$$

πr_n^2 is defined as the *effective area,* A_P of the piston-cylinder assembly, i.e. the quantity by which the applied force must be divided to derive the applied pressure. It is a function of the dimensions of both the piston and the cylinder. The effective load strictly includes the force due to the mass of the annular column of fluid between the neutral surface and that of the true piston, but this is normally negligible. Hence, the applied gauge pressure P ($P_1 - P_2$), i.e. the amount by which the pressure within the system exceeds the external pressure at the reference level (the base of the piston or an identified plane) , is to a good approximation given by :

$$P = \frac{W}{A_P} \qquad (5.6)$$

In practice a number of deviations from the ideal form are found in both pistons and cylinders. Therefore, in order to calculate the effective area from dimensional data, measurements are required which yield information on the roundness and straightness of the components as well as their absolute diameters.

From the theory of elastic distortion it can be shown that the variation of the effective area, A_P, of a simple piston-cylinder with applied pressure P is essentially linear,

$$A_P = A_0(1 + aP) \qquad (5.7)$$

where A_0 is the effective area for zero applied pressure, the deviations from linearity in practice being small. Also the dimensions of the components should be relatively large to reduce the uncertainties associated with diametral measurements to an acceptable level. Furthermore this method yields the value of the effective area at zero applied pressure and does not take into account the variation of the effective area of the assembly due to the elastic distortion of both piston and cylinder with applied pressure.

An estimate of the distortion coefficient, a, for the simple type of piston cylinder assembly can be calculated directly from dimensions and the elastic constants of the materials. However, due to the complexity of the forces acting on both components in any but the simplest designs, this method is somewhat limited.

For general purposes, these quantities are evaluated by comparing the pressure balance with a primary standard instrument, in a procedure often referred to as *cross-floating*, (See section on calibration of pressure measurement standards).

f) Corrections

In practice a number of corrections are required to determine gauge pressure using a dead weight pressure tester.

Temperature correction

The calibration certificate of a pressure tester will normally give the effective area value at a reference temperature of 20 °C. If the temperature of the piston-cylinder assembly in use is different from the reference temperature a correction is required .This is usually combined with the pressure distortion co-efficient a and expressed as :

$$A_{P,t} = A_{0,20}(1 + aP)\left[1 + (\alpha_p + \alpha_c)(t - 20)\right] \qquad (5.8)$$

where,

$A_{p,t}$ – the effective area of the piston cylinder assembly at applied pressure P and temperature t ,

$A_{0,20}$ –the effective area of the piston cylinder assembly at zero applied pressure and 20 °C,

a – pressure distortion co-efficient of the piston cylinder assembly,

α_p - linear expansion co-efficient of the piston,

α_c - linear expansion coefficient of the cylinder

Evaluation of force

The general equation for the evaluation of downward force for an oil operated dead weight pressure tester is given by :

$$W = g\left[\sum\left\{M\left(1 - \frac{\rho_a}{\rho_m}\right)\right\} + B + H\right] + S \qquad (5.9)$$

where,

W - net downward force exerted by the weights, and the piston assembly

g – local acceleration due to gravity,

M - conventional mass of the component parts of the load , including the piston,

ρ_a - density of ambient air,

ρ_m -density of the mass M, and can be significantly different for each load component,

B – correction due to fluid buoyancy acting on the submerged parts of the piston,

H – fluid head correction,

S – correction for surface tension

Air buoyancy correction

The factor $(1-\frac{\rho_a}{\rho_m})$ corrects for air buoyancy effects. It has a value of approximately 0.99985 when working in air at one atmosphere and with steel weights. If there are significant differences of the densities of the weights, weight carrier and the piston, the corrections are separately worked out and added together.

The density of ambient air depends on the atmospheric pressure, temperature, relative humidity and composition. For very accurate work these parameters are measured and the air density calculated from an empirical equation. The approximate density of ambient air is 1.2 kg/m^3.

Fluid buoyancy correction

The fluid buoyancy force correction is calculated as an upthrust equivalent to weight of the volume of fluid displaced by the submerged part of the piston. The volume of fluid concerned depends on the reference level chosen for specifying the applied pressure.

Fluid head correction

The output pressure of a dead weight pressure tester is usually obtained at a level different from the reference level of the tester. A correction is then required to take account of the difference in levels. It is more convenient to combine the fluid head correction with the fluid buoyancy correction, and the combined correction factor expressed as a load correction is given by :

$$H+B=(hA-v)(\rho_f-\rho_a) \qquad (5.10)$$

where,

h – diffrence in levels between the pressure output and reference plane of the pressure tester,

A – Nominal effective area of the piston,

v- volume of fluid displaced by the piston

ρ_f -density of the fluid

Surface tension effects

A correction to account for the surface tensional forces acting on the piston is included. This correction is given by :

$$S=s.C \qquad (5.11)$$

Where,

S – force due to surface tension,

s - surface tension of the fluid,

C – circumference of the floating element at the point of emergence from the fluid.

Summary

Taking all the above correction terms into account, the applied pressure at the specified reference level is obtained from the equation:

$$P = \frac{g\left[\sum\left\{m\left(1-\frac{\rho_a}{\rho_m}\right)\right\}+(hA-v)(\rho_f-\rho_a)\right]+s.C}{A_{0,20}(1+aP)\left[1+(\alpha_p+\alpha_c)(t-20)\right]} \qquad (5.12)$$

5.6.2 Portable pressure standard (Pressure calibrator)

A variety of portable pressure standards also known as pressure calibrators that use strain gauge, capacitance and piezo-resistive transducers are available from a number of manufacturers. Usually these consist of a portable pressure pump, pressure transducer assembly and associated electronics and display. These are very convenient for calibration of pressure gauges and transmitters used on line in a large number of process industries. However these instruments require frequent calibration against a secondary pressure standard maintained in a laboratory. Instruments ranging upto 800 kPa with an accuracy of ±0.5 per cent of the reading are available. Portable type dead weight pressure balances of the hydraulic type upto 70 MPa and pneumatic type upto 200 kPa are also in use.

5.7 Pressure measuring instruments

5.7.1 Liquid column instruments

a) Mercury barometers

Mercury barometers are generally used for measuring ambient pressure. There are two popular types, Fortin barometer and Kew pattern barometer.

Fortin barometer

A Fortin barometer(Figure 5.10) can be used only to measure ambient pressure over the normal atmospheric pressure range. The height of the mercury column is measured using a vernier scale. A fiducial point mounted in the cistern determines the zero of the vertical scale. The mercury level in the cistern can be adjusted up or down by turning a screw to squeeze a leather bag. In making a measurement the instrument is made vertical with the help of a spirit level mounted on it and the screw is turned until the mercury meniscus in the cistern just touches the fiducial point. The vernier scale is then adjusted to coincide with the upper mercury meniscus and the reading is read off the scale.

In addition to the corrections recorded in the calibration certificate, corrections are needed to take account of instrument temperature and value of gravitational acceleration. Details of these corrections are given in British Standard BS 2520.

Mercury barometers handled properly are very reliable instruments. They should be transported with extreme care.

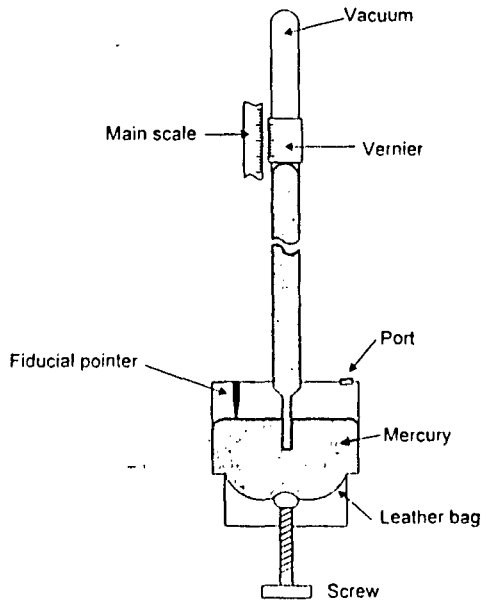


Figure 5.10- Fortin barometer

Kew pattern barometer

A version of the Kew pattern barometer known as the station barometer is similar to a Fortin barometer except that it has a fixed cistern. In this version the scale is contracted slightly in order to compensate for the varying mercury level in the cistern.

Kew pattern bench barometers are free standing and pressures from a few millibars to atmospheric can be measured. These use a pressure port and do not need total immersion calibration.

As in the case of the Fortin barometer, corrections are needed for changes in temperature and local gravitational acceleration. These are again given in the British standard BS 2520.

Precautions for handling of mercury barometers

Great care is needed in transportation of mercury barometers primarily to avoid changing their metrological properties and exposing people and the environment to toxic mercury vapour. For transportation they should be sealed in rupture and leak proof plastic bags.

The glass tube of a Fortin barometer can be broken if mercury is allowed to oscillate up and down, while it is being moved in upright position. To prevent this occurring or air entering the tube during transportation, the axial screw is turned until mercury has risen to within about 25 mm of the top of the tube. The barometer is then inclined slowly until mercury just touches the top of the tube, then continuing until the instrument is somewhere between horizontal and completely upside down.

Kew station barometers that do not have an axial screw should be treated similar to Fortin barometers and turned slowly until horizontal or upside down.

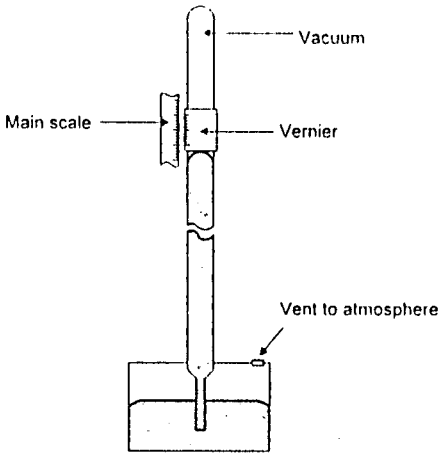


Figure 5.11- Kew pattern barometer

In the case of Kew bench type barometers mercury in the tube should be isolated from the atmosphere before transportation, either with the tube nearly empty or nearly full. Some designs provide transportation sealing screws to achieve this but sealing the pressure port is sufficient. Additional packaging is applied between the tube and the barometer's frame, when transporting with the barometer's tube nearly full. The barometer is transported in the normal upright position.

Risk of spillage can also be reduced by ensuring that mercury barometers are placed in locations where they can not be easily accidentally damaged.

b) U tube manometer

A U tube manometer is one of the most simple instruments used for measurement of pressure .It consists of a tube made from glass or other material (PVC or polythene) bent to the shape of a U and filled with a liquid, Figure 5.12.

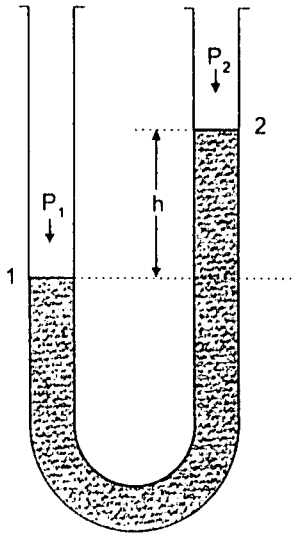


Figure 5.12- U-tube manometer

The fundamental principle that the absolute pressure on the same horizontal plane in a given liquid is constant is used in the U tube manometer. In mathematical form this principle is expressed in the following equation :

$$P_1 = P_2 + h.\rho.g \qquad (5.13)$$

Where,

P_1 and P_2 - Pressure at points 1 and 2

h - the difference of height between the fluid levels of the two limbs,

ρ - the density of manometric liquid,

g - local acceleration due to gravity

If $P_1 = P_2$, that is when both ends of the U-tube are subjected to the same pressure, the levels of the liquid column will be at the same horizontal level. If however, one limb is at a higher pressure than the other, the liquid column in that limb is depressed. The pressure difference between the two limbs is read off as the difference in heights of the liquid columns in the two limbs.

Mercury, water and oil are all used in various designs of manometer. For measuring large pressure differences, mercury is frequently used as its density is over 13 times greater than that of water or oil and thus, for a given pressure, it requires a much shorter column. Density of mercury is also considerably more stable than that of other liquids.

Water or oil liquid columns are used to measure low gauge and differential pressures. In some designs the manometer is inclined as this increases its sensitivity, the fluid having further to travel along the inclined column to achieve a given vertical movement. The traditional units for this type of measurement were *inches of water* or *millimetres of water*, but as units they are poorly defined and as mentioned earlier their continued use is strongly discouraged .

5.7.2 Mechanical deformation instruments

a) Bourdon tube gauge

A metallic tube of elliptical cross-section that is bent to form a circular arc is the sensing element of a Bourdon tube dial gauge. The application of a pressure to the open end of the tube straightens it out. The movement of the free end of the tube is amplified mechanically using gears and levers to operate a pointer. Bourdon tube dial gauges operate at pressures up to about 1.5 GPa and a typical mechanism is shown in Figure 5.13.

Bourdon tube dial gauges are most commonly used for measuring gauge pressure but can also be used to measure absolute pressures by sealing the case. Differential pressure measurement is achieved by use of a second tube whose movement is mechanically subtracted from the main tube.

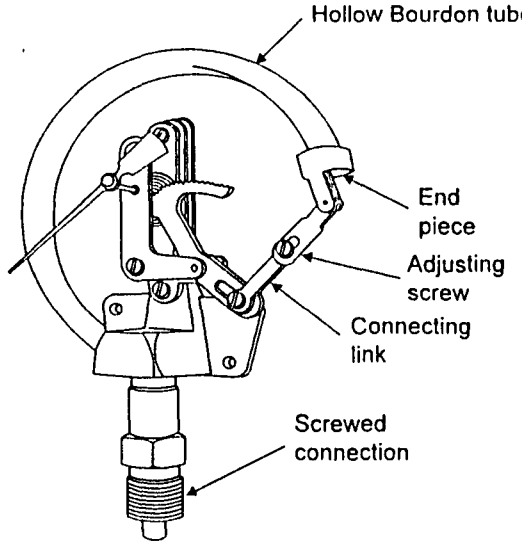


Figure 5.13- Mechanism of a Bourdon tube pressure gauge

b) Diaphragm gauge

The diaphragm dial gauge is similar to a Bourdon tube dial gauge except that the moving element is a diaphragm. Its movement is transmitted through a connecting rod to an amplifying lever and gears that rotate a mechanical pointer.

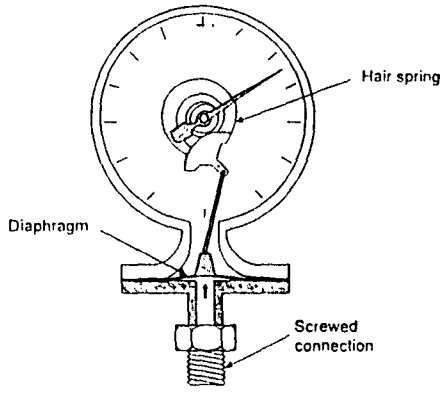


Figure 5.14- Diaphragm dial gauge mechanism

Differential pressure is easily measured by applying it across the diaphragm.

c) LVDT

A linear variable differential transformer (LVDT) pressure transducer (Figure 5.15) consists of a cylinder of ferromagnetic material moving inside a metallic tube. The end of the cylinder is attached to a deflecting component such as a diaphragm or bellows to which the test pressure is applied. Three coils are mounted on the tube. The central primary coil is excited with an alternating voltage. The two sensing coils, one on either side are used for signal collection. As the magnetic cylinder moves within the tube, the magnetic field coupling, between the primary and secondary coils changes. With suitable electronics, which may include temperature compensation, a linear relationship between cylinder position and output can be obtained. Sensors of this type are used in pressure transducers operating between pressures of about 10 mPa to 10 MPa.

The cylinder end may need support as the attachment of the pressure-sensing element increases the weight and stiffness of the LVDT. LVDT pressure transducers are more commonly available as gauge or differential pressure devices. Absolute pressure units are more complex.

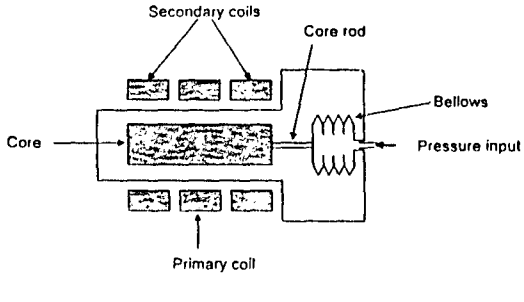


Figure 5.15-LVDT pressure transducer

d) Piezo electric devices

When certain types of crystalline materials are subjected to an external pressure, an electric charge proportional to the rate of change of applied pressure is generated on the crystal

surface. A charge amplifier is used to integrate the electric charges to give a signal that is proportional to the applied pressure. The response is very fast, making these sensors suitable for dynamic pressure and peak pressure measurement. However these sensors can not be used for measurement of steady pressure values.

Early piezoelectric transducers used naturally grown quartz but today mostly artificial quartz is used. These devices are often known as *quartz pressure transducers*. A piezoelectric crystal being an active sensor requires no power supply. Also the deformation of the crystal being very small makes them to have good high frequency response.

The major use of this type of sensor is in the measurement of very high frequency pressure variations (dynamic pressure) such as in measuring pressures in combustion chambers of engines. They are also capable of withstanding high over-pressures.

5.7.3 Indirect instruments

a) Thermal conductivity gauges

Pirani gauge

In a Pirani gauge, the energy transfer from a hot wire through a gas is used to measure the pressure of the gas. The heat energy is transferred to the gas by conduction and the rate of transfer depends on the thermal conductivity of the gas. The performance of these instruments therefore is strongly dependant on the composition of the gas.

In the traditional configuration, a thin metal wire loop is sealed at one end of a glass tube whose other end is exposed to the gas. Tungsten, nickel, iridium or platinum is used as the material of the wire. In another type, the gauge sensor is a micro-machined structure, usually made from silicon covered by a thin metal film, such as platinum.

The wire or the metal film is electrically heated and its resistance, which is dependant on its temperature, is measured by incorporating the sensor element in a Wheatstone bridge circuit. There are three common operating methods: constant temperature method, constant voltage bridge, and the constant current bridge.

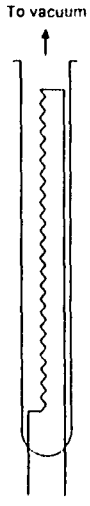


Figure 5.16-Pirani gauge

The main drawback of Pirani gauges is their strong gas composition dependence and their limited accuracy. The reproducibility of Pirani gauges is usually fairly good as long as no heavy contamination occurs. The measuring range of Pirani gauges is approximately from 10^{-2} Pa to 10^{5} Pa, but the best performance is usually obtained between about 10^{-1} Pa and 10^{3} Pa. A variant of the Pirani gauge known as *convection enhanced Pirani gauge* is able to measure pressures in the range 10^{-2} Pa to 10^{5} Pa.

b) Ionization gauges

A convenient method of measuring very low absolute pressures of a gas is to ionise the gas and measure the ionisation current. Most practical vacuum gauges use electrons of moderate energies (50 eV- 150 eV) to perform the ionisation. The resulting ion current is directly related to pressure and a calibration is performed to relate the gas pressure to ionisation current. However these can only be used over a finite range of pressures. The upper pressure limit is reached when the gas density is so large that when an ion is created it has a significant probability of interacting with either a neutral gas molecule or free electrons in the gas so that the ion is itself neutralised and cannot reach the collector. For practical purposes this can be taken as 10^{-1} Pa. The lower pressure limit of an ionisation gauge is around 10^{-6} Pa. This limit is reached when either electric leakage currents in the gauge measuring electronics become comparable to the ion current being measured or when another physical influence factor (e.g. extraneous radiation) gives rise to currents of similar magnitude.

Two types of ionisation gauges are in widespread use, the *hot cathode* ionisation gauge and the *cold cathode* ionisation gauge.

Triode gauge

The triode gauge is a hot cathode type gauge. The gauge has been originally developed from the electronic valve. Electrons are emitted from a hot filament along the axis of the cylindrical grid, Figure 5.16. The ions are created mainly inside the grid and are attracted to the cylindrical anode around the grid. The usual pressure range of the instrument is about 10^{-1} Pa to 10^{-6} Pa. A special design, the Schultz-Phelps gauge, can operate in the approximate range 10^{2} Pa to 10^{-2} Pa.

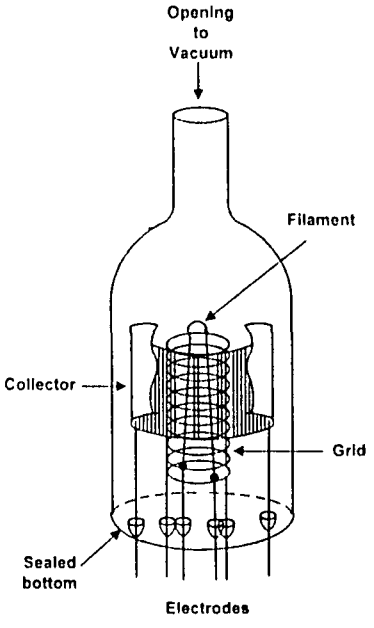


Figure 5.17-Triode gauge

Bayard-Alpert gauge

In the Bayard-Alpert design, hot filament is outside of the cylindrical grid, Figure 5.18. Ions are created mainly inside the grid and are collected on an axial collector wire. Some of the electrons produced as a result of the ionisation of the gas molecules will generate X-rays when they hit the grid. X-rays hitting the collector may eject electrons from the surface and they will be indistinguishable from ions arriving at the collector. Due to the much smaller solid angle subtended by the collector wire fewer of the X-rays will strike the collector, resulting in a significantly lower pressure limit than for the triode gauge.This is the most common

configuration for a hot filament ionisation gauge.The pressure range is roughly 10^{-1} Pa to 10^{-9} Pa.

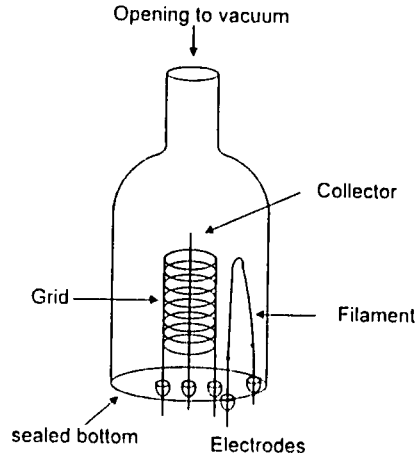


Figure 5.18- Bayard-Alpert gauge

Penning gauge

The Penning gauge is a cold cathode type gauge. A schematic of the gauge head is shown in Figure 5.19.In this gauge both electric and magnetic fields are used to generate and collect the ions. The anode may take the form of ring or cylinder. When the electric field is high enough (a few kV DC),a gas discharge is initiated by the use of a miniature ultra violet light source. Emission of electrons then takes place from the cathode plates. The loop anode collects ions. The pressure range is approximately 10^{-1} Pa to 10^{-7} Pa.

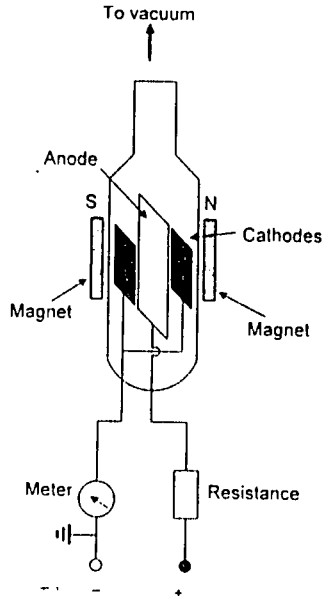


Figure 5.1-Penning gauge

6 Measurement of force

6.1 Introduction

The concepts of force measurement are outlined in this chapter. The calibration of force measurement standards and test instruments is described in Chapter 13.

6.2 Primary Standard

The primary standard of force measurement is the dead weight force standard machine. There are several types of these machines. The basic principle of the dead weight force standard machine is illustrated in Figure 6.1. In this standard, the gravitational force exerted on a set of masses is utilised to generate the force. The force **F** generated by a mass **M** installed in a force standard machine under gravitational acceleration **g** is given by the following equation:

$$F = Mg\left[1 - \frac{\rho_a}{\rho_M}\right] \qquad (6.1)$$

The factor within the square bracket corrects for the air buoyancy effect. ρ_a and ρ_M are the densities of air and the mass respectively. It can be seen from equation 6.1 that to determine F an accurate value for the acceleration due to gravity (g) is required.

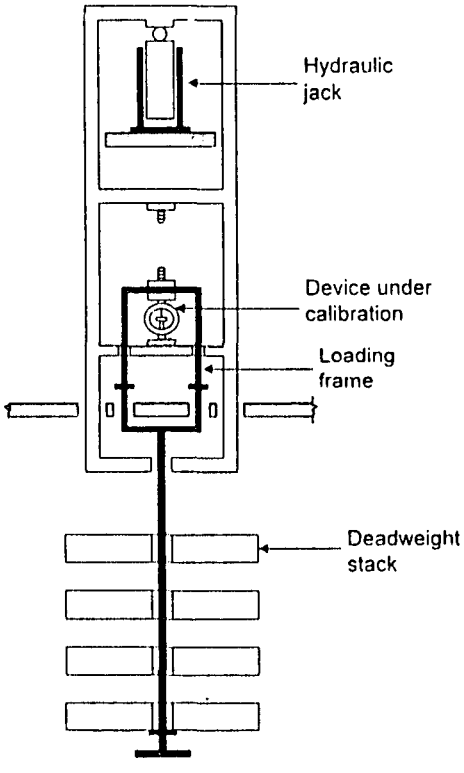


Figure 6.1-Principle of dead weight force standard

6.3 Secondary Standards

6.3.1 Lever or hydraulic force standard machines

Higher capacity force standard machines generally use a hydraulic or mechanical lever system to increase the force generated by a set of dead weights. These machines are classified as secondary force standards as they require calibration against a primary standard. Usually a number of load cells in parallel are used as the transfer standard. Forces as high as 20 MN have been generated, using these machines. The schematic of a hydraulic force standard machine is given in Figure 6.2.

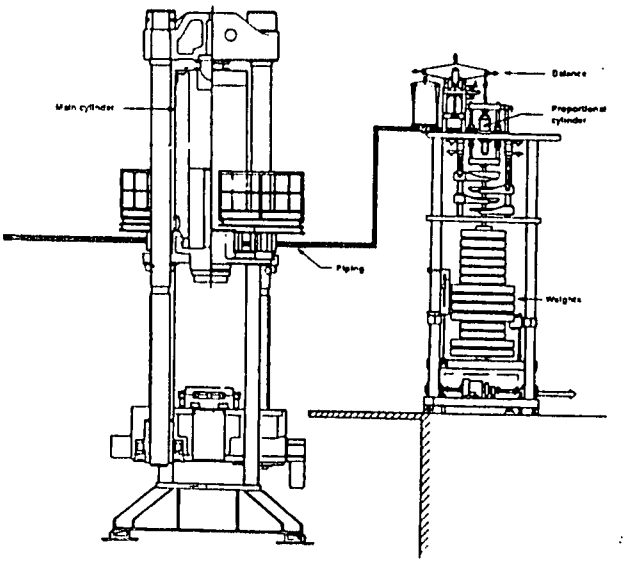


Figure 6.2-Schematic of hydraulic force standard machine

6.3.2 Proving ring

A proving ring is a ring made from alloy steel. The relationship between the central deflection of the ring and the applied load at a specified temperature is used as the force standard. In a good quality proving ring this relationship remains unchanged for a considerable period of time if the ring has not been subjected to overloading, shock or any other deleterious effect. A proving ring can be used in either compression or tensile modes. The principle of operation of a proving ring is illustrated in Figure 6.3.

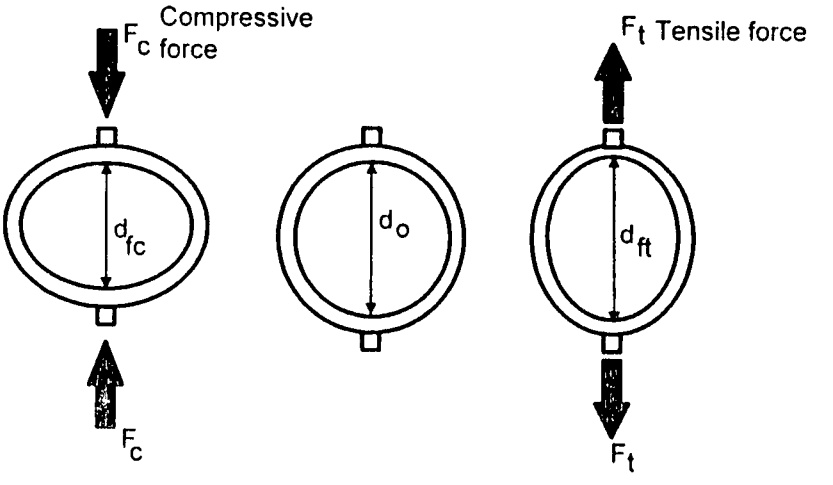


Figure 6.3-Principle of operation of proving ring

A proving ring has to be calibrated in a dead weight force standard machine to establish the force–deflection relationship. When carefully used proving rings are excellent secondary standards.

Secondary standard proving rings upto 2 MN capacity having relative uncertainties of the order of ±0.01 percent of full scale are commercially available.

6.3.3 Load cell

Although load cells are commonly used for force measurement in a number of instruments, such as universal testing machines, weigh bridges, cable testers etc., those having the required uncertainty and stability for use as secondary standards are also available from a number of manufacturers. The principle of operation of load cells is given in the section on force measuring instruments. Secondary standard load cells up to 5 MN having relative uncertainties of ± 0.05 percent of full scale are available commercially.

6.3.4 Universal calibrator

An often-used instrument to transfer forces between a secondary standard and a working standard or a transducer is the universal calibrator. In this instrument two devices (e.g. a proving ring and a load cell) can be positioned and loaded in series with an applied force.

The calibrator consists primarily of three major parts, the stationary frame, the movable frame or yoke and the hydraulic jack (Figure 6.4). The stationary frame is fixed on the ground. The movable frame can be adjusted to suit the length of the reference standard. In addition the upper platen of the yoke can also be moved up and down to allow for different sized test items. The upper platen is also provided with a ball seat which allows a hardened steel ball to be positioned between the yoke platen and the reference standard (proving ring) to assure axial loading.

The lower platen of the stationary frame and the lower yoke platen are provided with center holes. These holes provide a means by which the test items can be attached to the machine with suitable studs or tension members. The machine is designed to minimize friction and non-axial loading which usually give rise to large errors.

A special hydraulic jack activated by a precision two-speed pump advances the ram quickly until a designated pressure (usually about 5 MPa) is reached and then slowly until the desired load is achieved. The leak rate of the jack is very small does not affect precise calibrations. The machine can quite easily be adapted to calibrate either in tension or compression mode.

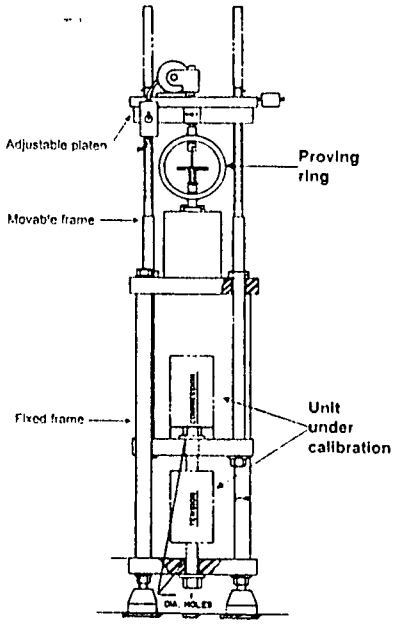


Figure 6.4-Universal force calibrator (Source : Morehouse Instrument Company,U.S.A)

6.4 Force measuring instruments

6.4.1 Characteristics of force measuring devices

The typical output characteristic (Response curve) of a force measurement transducer is shown in Figure 6.5. In this diagram the output of the transducer against the applied force is plotted as the applied force is increased from zero to the rated capacity and returned to zero. A number of significant features of a force measuring transducer or system are illustrated in this diagram.

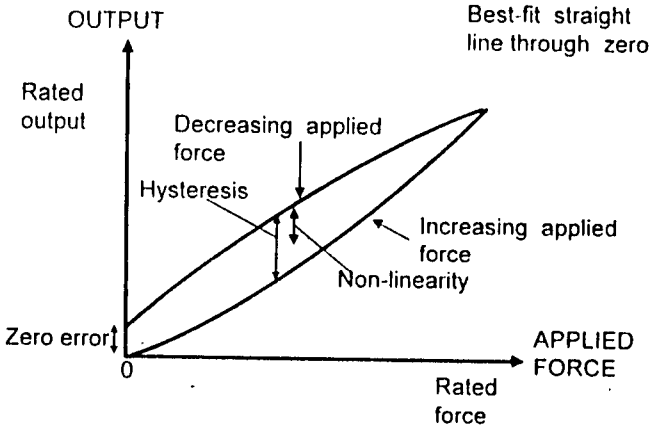


Figure 6.5 Typical response curve of a force measuring transducer

The deviation of the response from a straight line is magnified in this diagram for purposes of clarity. A commonly used method of characterising a force measuring system is by the use of a best-fit straight line passing through zero.

a) Rated capacity

The *rated capacity* is the maximum force that a force transducer is designed to measure.

b) Non-linearity

Deviations from the best-fit line are referred to as *non-linearity* and usually the largest deviation is given in the specifications of a transducer.

Hysteresis

The difference of the output readings between the increasing and decreasing forces at any given force is defined as the *hysteresis*. The largest value of hysteresis is usually at mid range of the system. Sometimes the non-linearity and hysteresis are combined in a single figure. This is usually done by drawing two lines parallel to the best-fit line enclosing the increasing and decreasing curves. The difference of output between the lines is halved and stated as $\pm$ *combined error*.

c) Creep and creep recovery

A force measuring system usually takes some time to adjust to a change in applied force. This is known as *creep* and is usually defined as the change of output following a step increase in force from one value to another. Most manufacturers specify the creep as the maximum change of output over a specified time after increasing the force from zero to the rated force e.g. 0.04 percent of rated output over 30 minutes. *Creep recovery* is the change of output following a step decrease in the applied force, usually from rated force to zero. Both *creep* and *creep recovery* values are dependent on the time duration of the applied force at the rated capacity or zero respectively.

d) Frequency response

The *frequency response* of a transducer or system is the quantification of its ability to measure forces varying in time. i.e. dynamic forces. The frequency response is defined as the highest sinusoidal frequency of applied force which the transducer or system can measure to a specified accuracy.

e) Fatigue life

If a transducer is used for measurement of fluctuating forces, then its *fatigue life* should be considered. *Fatigue life* is defined as the number of total full cycles of force which may be applied before the measurement uncertainty is altered beyond specified limits.

f) Temperature effects

Both the zero and rated output of a force transducer are affected by a change in the temperature. The *temperature co-efficient of the output at zero force* and *temperature co-efficient of the sensitivity* are measures of this effect for a given transducer or system.

Other influence quantities such as humidity, pressure, electrical or radio frequency interference may have similar effects to that of temperature and should be taken into account in the design of force measurement systems.

6.4.2 Strain gauge load cell

The most commonly used instrument for force measurement is the electrically operated strain gauge load cell. Strain gauge load cells are available for measurement of tensile, compressive and shear forces. They are also used for measurement of torque. The rated capacity of strain gauge load cells range from 5 N to 50 MN.

Principle of operation

A metallic body deforms on the application of a force on it. A tensile force applied on a cylindrical body is shown in Figure 6.6.There is an increase of the length as well as a small decrease in the diameter. When the applied force is removed the body returns to its original

dimensions, provided the elastic limit of the material had not been exceeded. The longitudinal as well as lateral deformations are sensed by strain gauges bonded to the surface of the cylinder.

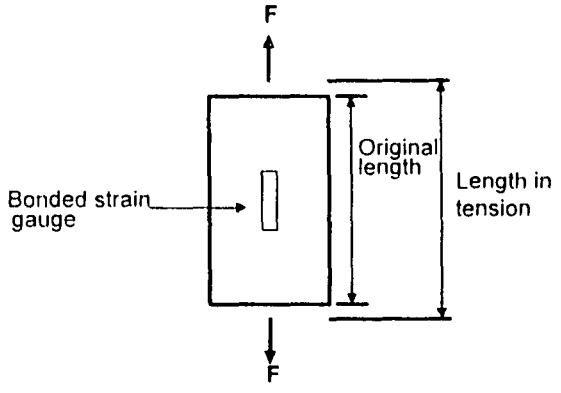


Figure 6.6 Basic principle of the elastic transducer element

a) Elastic element

A number of different shapes of elastic elements are used depending on the range of force to be measured, dimensional limits, final uncertainty and cost of production. A range of commonly used types and their rated capacities are given in Figure 6.7.

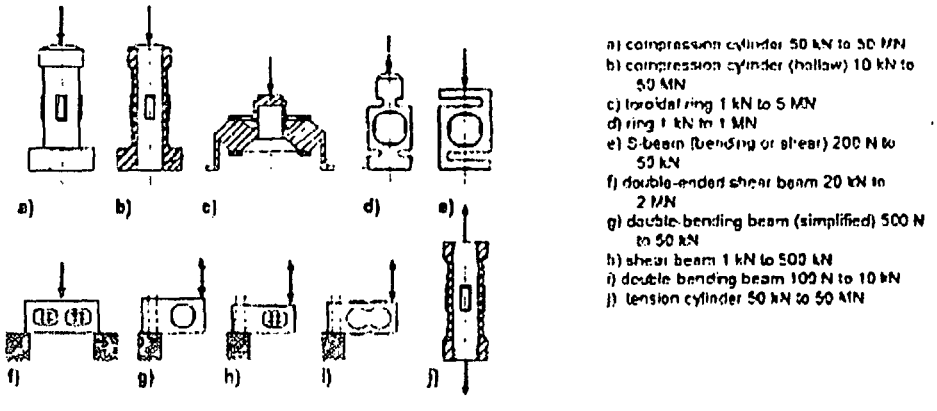


Figure 6.7-Typical strain elements and their usual rated capacities (Source: Guide to the Measurement of Force, Institute of Measurement & Control, U.K)

A material having a linear relationship with stress and strain, with low hysteresis, low creep and high level of repeatability in the working range is used as the material of construction. Usually stainless steel, tool steel, aluminium or beryllium copper is used. A special heat treatment including sub zero temperature cycles is required to achieve stability.

b) Resistance strain gauge

In an electrical resistance strain gauge, the change of resistance of an electrical conductor arising from change of its length and cross section is utilised to detect strain. When a strain gauge is bonded to a metallic substrate, the changes of strain in the substrate will be reflected as a change in resistance of the gauge. This is measured and used to determine the applied force by calibrating the device.

The change in gauge resistance (δR) is related to the change in gauge length (δL) by the gauge factor k:

$$k = \frac{\delta R/R}{\delta L/L} \qquad (6.2)$$

Where:

R – gauge resistance and L - gauge length

For a strain gauge to be useful it should have a relatively high gauge factor, so that small changes in strain give rise to large changes in resistance. Also the gauge factor must be constant over the rated range of applied strains. In addition it must not change significantly over time.

Copper-nickel, nickel-chromium, nickel-chromium-molybdenum and platinum tungsten alloys generally referred to by their trade names are the most common materials used for the manufacture of strain gauges.

A large variety of strain gauges are available for various applications .A strain gauge is usually designed to measure the strain along a clearly defined axis so that it can be properly aligned with the strain field.

The nominal resistance of the strain gauge varies with the type and application. Wire gauges have resistances in the range of 60 Ω to 350Ω, foil and semiconductor gauges from 120Ωto 5 kΩ and thin film types around 10 kΩ.

Foil strain gauge

The foil strain gauge is the most commonly used type and a number of different designs are shown in Figure 6.8

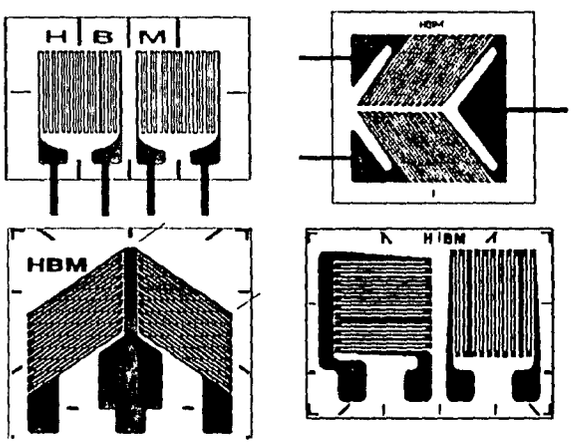


Figure 6.8-Typical metal foil strain gauges (Source : Hottinger Baldwin Measurements)

The foil strain gauge is constructed by bonding a sheet of thin rolled metal foil, 2-5 μm thick, on a backing sheet of 10-30 μm thick and photo-etching the measuring grid pattern including the terminal tabs or by cutting the grid from foil using accurate dies. In photo etching, production techniques similar to those used in the integrated circuit manufacturing industry are used. Accurate and cheap production of complex or very small grid patterns is possible using these processes.

The backing provides electrical insulation between the foil and the elastic element, facilitates handling and presents a readily bondable surface. Typical backing materials are epoxy, polyamide and glass-reinforced epoxy phenolic resins. Some gauges come with an adhesive layer applied to the backing to make it easy for application of the gauge.

In high- precision load cells, the epoxy or epoxy-derived backing material is preferred because of its superior performance especially creep and low level of moisture absorption

compared to polyamide type plastic, although epoxy based material is difficult to handle due to its brittle nature. Typical specifications of foil gauges are given Table 6.1.

Table 6.1-Typical specifications of foil and semi-conductor strain gauges

Characteristic	Typical specifications	
	Foil gauge	**Semi conductor gauge**
Gauge length, mm	2, 5 or 8	-
Gauge factor	Approximately 2. This is usually quoted individually with the gauge or pack of gauges to two decimal places.	100 to 150 Individually calibrated
Gauge factor temperature co-efficient, %/ K	± 0.015	-
Resistance,Ω	120, 350,600, and 1000	120
Measurable strain, percent	2 to 4	upto 5
Fatigue life, strain reversals	upto 10^7 at 0.1 % strain	upto 10^6
Temperature range, °C	-30 to +180	-
Temperature compensation: General purpose steels, per K Stainless steels, per °C: Aluminum, per °C	 11×10^{-6} 17×10^{-6} 23×10^{-6}	

Normally strain gauges are available with automatic compensation that matches the temperature expansion co-efficient of one of the three most commonly used materials. Some manufacturers also supply gauges compensated for use on titanium, magnesium alloys and plastic materials. When a temperature compensated gauge is bonded to a material for which the gauge has been matched, the apparent strain due to temperature variations on the gauge can be held down to less than 1.5 micro strain per °C over a temperature range from –20 °C to + 150 °C.

Semiconductor strain gauge

Semi conductor strain gauges consist of a strip conductor made from a single crystal of P-type or N-type silicon. Due to the high piezo-resistive effect of these materials, their electrical conductivity is highly dependant on the applied strain. The gauge factor of a semiconductor strain gauge is typically 100-150 compared to typically 2-4 of that of a wire or foil strain gauge. The output from semiconductor gauges is non-linear with strain. However their fatigue life is extremely long and they exhibit only minimal creep or hysteresis.

Due to the relatively high temperature co-efficient of these gauges, careful matching of the gauges is required on any given load cell. P-type gauges exhibit positive gauge factors and N-type gauges have negative gauge factors. By combining a P-type with a N-type a

temperature compensated pair can be obtained. Usually such pairs are selected by computer matching during manufacture, but compensation circuitry may still be required on the completed transducer. This type of gauge is widely used on small force transducers, accelerometers and pressure sensors. Typical specifications are given in Table 6.1.

Thin film strain gauge

Thin films of metals or alloys are deposited on the elastic element using radio frequency sputtering or thermal evaporation techniques for fabrication of thin film strain gauges. The gauge is insulated from the substrate by deposition of a layer of insulating material such as alumina. Several stages of evaporation and sputtering may be used resulting in several layers of material. A number of thin-film strain gauge force transducers are available covering a range of 0.1 N to 100 N in the form of single- or double- bending beam configuration.

Wire strain gauge

The wire strain gauge made from a wide range of materials is used extensively for high temperature transducers and stress analysis. The wire is typically 20-30 μm in diameter and may be bonded to the substrate using ceramic materials. The 'free' form where the wire is looped around insulated pins mounted on the elastic member is less commonly used. The wire strain gauge is the original type of resistance strain gauge, though now widely replaced by cheaper foil or thin film types

Instrumentation

The resistance change of a strain gauge is detected by incorporating it in a Wheatstone bridge configuration as shown in Figure 6.9. To maximise the response of the load cell one or more strain gauges aligned to respond to the longitudinal strain and another set aligned with the transverse strain are connected in the arms of the bridge. This configuration also minimizes the effects of influence quantities such as temperature that act equally on all the gauges. The resistance change is detected by measuring the differential voltage across the bridge.

The voltage ouput from the bridge when excited by an input voltage is linearly related to the resistance changes of the strain gauges. The output voltage is proportional to the product of the strain and the excitation voltage. The output of a bridge is usually rated to 2 mV/V (2 millivolts output per 2 volts applied),but this can range from 1 mV/V to 4 mV/V.

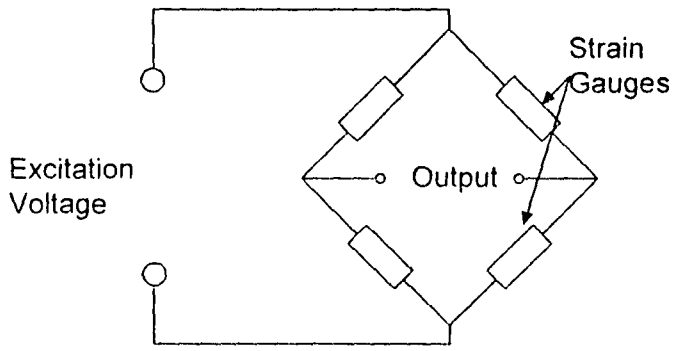


Figure 6.9-Basic arrangement of four strain gauges

To realise the full capability of the strain gauge load cell, several correction and compensation components are needed. A circuit diagram incorporating these components as used in a typical commercial load cell is given in Figure 6.10

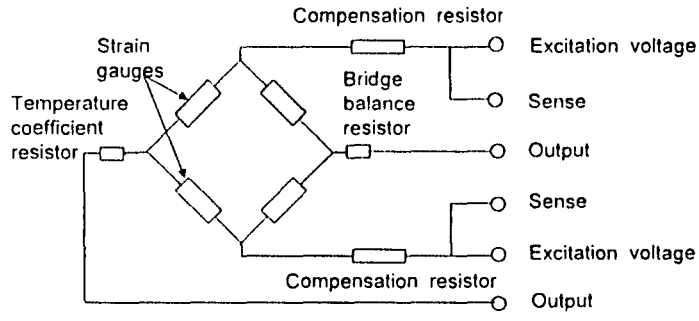


Figure 6.10-Typical commercial load cell circuit

The bridge is usually supplied with a direct current (DC) voltage. The output is amplified using an instrumentation amplifier. This method has wide frequency bandwidth, high stability and relatively low cost. Alternatively the bridge may be excited by an AC voltage, having a sine, square or other waveform. In this case the output is processed through an AC amplifier, a demodulator, filter and DC amplifier. An AC excitation system has a higher immunity to thermo-electric effects in the transducer and thermal effects in the instrumentation. They also have high noise rejection, good zero force output stability and ease of achieving isolation between the signal output and the load cell. However these systems tend to be costly due to the relatively complex measuring chain.

6.4.3 Hydraulic load cell

In a hydraulic load cell the load cell cavity is filled with fluid (usually oil) and given a pre-load pressure. The application of a force to the loading member increases the fluid pressure, which is measured by a pressure transducer.

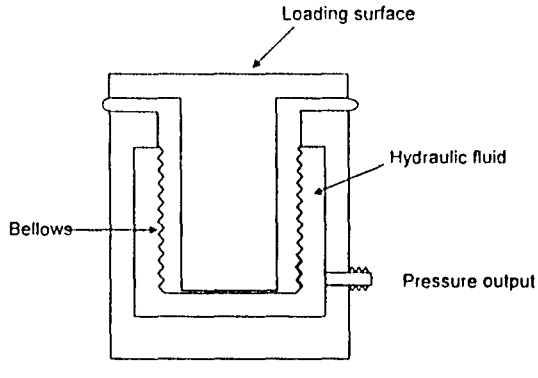


Figure 6.11-Typical hydraulic load cell

Hydraulic load cells are inherently very stiff, deflecting only about 0.05 mm under full force conditions. Capacities of up to 5 MN are available, although most devices are in the range of 500 N to 200 kN. The pressure gauge can be mounted several meters away from the load cell by using a special fluid-filled hose. In systems where more than one load cell is used a specially designed totaliser unit is employed. No external power is needed to operate hydraulic load cells and they are inherently suitable for use in potentially explosive atmospheres. Both tension and compression devices are available. Uncertainties of around 0.25per cent of full scale can be achieved with careful design and favorable application conditions. Uncertainties for total systems are more realistically 0.5-1% of full scale. The cells are sensitive to temperature changes and usually have facilities to adjust the zero output reading, the temperature coefficients are of the order of 0.02 per cent to 0.1 per cent per ^{o}C.

6.4.4 Pneumatic load cell

The operating principle of a pneumatic load cell is similar to that of a hydraulic load cell. The force applied to one side of a piston or a diaphragm of flexible material is balanced by

pneumatic pressure applied on the other side. The counteracting pressure is proportional to the force and is displayed on a pressure dial.

6.4.5 Elastic devices

The 'load column' a metal cylinder subjected to a force along its axis, is a simple elastic device used for measuring forces. The length of the cylinder is measured directly by a dial gauge or other technique, and an estimate of the force is made by interpolating between the lengths measured for previously applied known forces.

The proving ring described earlier is functionally very similar except that the element is a circular ring, and the deformation is usually measured across the inside diameter. These transducers have the advantage of being simple and robust, but the main disadvantage is the strong effect of temperature on the output. Such methods find use in monitoring the forces in building foundations and other similar applications.

6.4.6 Capacitive load cell

In capacitive load cells a capacitance sensor is used to detect the displacement of an elastic element. A parallel plate capacitor is used in most cases. In some cases the change of length of a spring as force is applied is used to change the gap between the plates, thus producing a change in the capacitance.

6.4.7 Optical strain gauge

In an optical strain gauge, the change in length of an optical fibre is utilised to detect strain.

The deformation of the elastic force-bearing member with the optical strain gauge bonded to it will result in length changes in the optical fibres. If two optical strain gauges experiencing different strain levels are fed with monochromatic light then the phase difference between the two beams emerging from the gauges, in number of half wavelengths, is a measure of the applied force. The advantage of an optical strain gauge is that they are immune to interference by electric and electromagnetic fields.

6.4.8 Magnetic transducer

The best known magnetic type load cell transducer is the *Pressductor* cell developed by ASEA of Sweden. In this transducer the change of permeability occurring in a magnetic core due to an applied force is utilised. The principle of the *Pressductor* is shown in Fig 6.12.

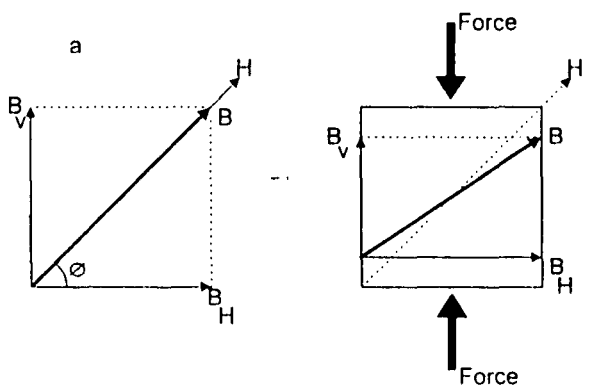


Figure 6.12-Magnetic principle of the *Pressductor* transducer

A square sheet of transformer iron is magnetised along one diagonal. The material being magnetically isotropic the magnetic flux density vector (**B**) is parallel to the magnetic field vector (**H**) and the horizontal and vertical components $B_V = B_H$. When vertical forces are applied anisotropy caused by magneto-elastic effects decreases the permeability in the direction of the forces and $B_V \leq B_H$.

The *Pressductor* transducer consists of a laminated iron core with two perpendicular windings as shown in Figure 6.13. An alternating current through the primary winding sets up

an alternating magnetic field in the core. However under no load condition, no voltage is induced in the perpendicular secondary winding. When a force is applied to the core the change in permeability causes the magnetic flux lines to change the angle (φ) generating a voltage in the secondary winding. The induced voltage is directly proportional to the applied force.

The calibration curve of the *Pressductor* is principally S shaped and linearization is needed to obtain high accuracy. *Pressductor* load cells having relative uncertainties of 0.05 per cent of full scale up to 20 tonne-force and 0.1 per cent up to 160 tonne-force are commercially available.

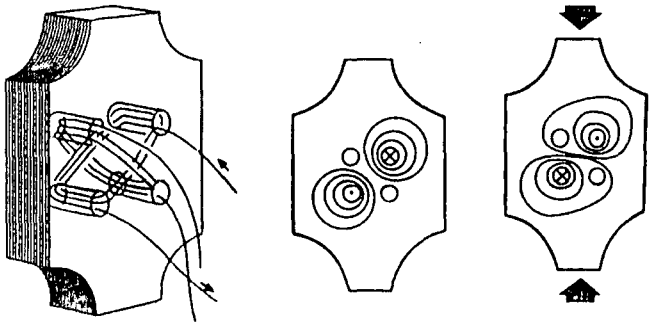


Figure 6.13-The Pressductor **transducer (Source: Electronic weighing by Ellis Norden, Butterworth & Helnemann)**

6.4.9 Vibrating strings transducer

The principle of operation of an vibrating strings transducer is illustrated in Figure 6. 14. The vibrating strings or wires (**B**) are placed in the air gap of two permanent magnets, and each of them is connected to an electronic oscillator circuit, which causes the strings to vibrate at their natural frequency (f_0).

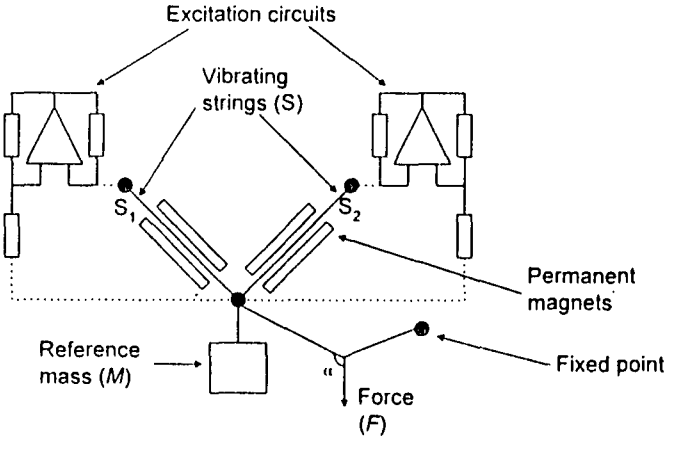


Figure 6.14-Vibrating strings transducer

The strings are pre loaded through a reference mass (M), and when the unknown force (F) is applied to the load connection through a string at a certain angle (α), the left string (S1*)* will be exposed to an increased tensional force, which increases the natural frequency (f_1) of that string, whereas the other string (S2) will lower its natural frequency (f_2), due to the decrease in the tensional force.

The difference between the two frequencies (δf*)* = (f_1-f_2) is thus proportional to the applied force (F).The strings are connected to an electronic circuit, which converts the frequency difference (δf) to a pulse train. A direct force reading is achieved by sampling the pulse train in a pulse counter during a predetermined time.

As the vibrating strings load cell compares the unknown force with a known reference force (M), it is independent of the earth's gravity. It has a high linearity and accuracy, and is reported to have extreme long term stability. This transducer is used in laboratory scales and other scales for smaller weights. Industrial applications include platform and belt conveyor scales.

6.4.10 Piezoelectric transducer

When certain types of crystalline materials are subjected to a force, an electric charge proportional to the rate of change of the force is generated on the crystal surface. A charge amplifier is used to integrate the electric charges to give a signal that is proportional to the applied force .

Early piezoelectric transducers used naturally grown quartz but today mostly artificial quartz is used. These devices are often known as *quartz force transducers*. A piezoelectric crystal being an active sensor requires no power supply. Also the deformation of the crystal being very small makes them to have good high frequency response.

When packaged as a load washer and compressed under a force of 10 kN a typical piezoelectric transducer deflects only 0.001 mm. The high frequency response (up to 100 kHz) enabled by this stiffness and the other inherent qualities of the piezoelectric effect makes piezoelectric crystal sensors very suitable for dynamic measurements

Piezoelectric sensors operate with small electric charges and require high impedance cable for the electrical interface. It is important to use the matched cabling supplied with a transducer. A small leakage of charge known as drift is inherent in the charge amplifier. Piezoelectric force transducers are ideally suited for dynamic measurements. Extremely fast events such as shock waves in solids, or impact printer and punch press forces can be measured with these devices when otherwise such measurements might not be achievable. However they are not very suitable for static measurements. When measurements are taken over a period of minutes or even hours they are said to take 'quasi-static' measurements.

Piezoelectric crystal sensors are suitable for measurements in laboratories as well as in industrial settings. The measuring range is very wide and the transducers survive high overload (typically > 100 per cent of full-scale output). The sensors' small dimensions, large measuring range and rugged packaging make them very easy to use. They can operate over a wide temperature range and survive temperatures of up to 350°C.

6.4.11 Linear variable differential transducer (LVDT)

The linear variable differential transducer (L VDT) is essentially a transformer that provides an alternating current (AC) output voltage as a function of the displacement of a movable magnetic core. An LVDT is sometimes used within a load cell to measure the displacement of an elastic element instead of using strain gauges. The lack of friction and the low mass of the core results in high resolution and low hysteresis, making this device ideal for dynamic measurement applications.

7 Measurement of temperature

7.1 Introduction

A description of the temperature scales and principle of operation of a number of types of thermometers are given in this chapter. The calibration of thermometers is dealt with in Chapter 14.

7.2 Thermodynamic scale

Temperature is the degree of hotness of an object and is governed by the laws of thermodynamics. The temperature scale based on the first and second laws of thermodynamics is known as the thermodynamic temperature scale. The lowest limit of the thermodynamic scale is absolute zero or 0 kelvin (K). Since the scale is linear by definition only one other non-zero reference point is needed to establish its slope. This reference point was originally defined as the freezing point of water (0 °C or 273.15 K) .In 1960 the reference point was changed to a more precisely reproducible point, namely the triple point of water (0.01 °C).

However measurement of temperature on the thermodynamic scale is hardly suitable for practical thermometry. In practice there are three main reasons:

a) It is difficult to measure thermodynamic temperatures. Apart from the technical elaboration required it could take days if not weeks to measure a single thermodynamic temperature.

b) In the determination of temperatures on the thermodynamic scale large systematic errors occur though these have been minimised in recent years.

c) The resolution or repeatability of thermodynamic thermometers is not as good as that achieved by many other empirical thermometers.

For these reasons all practical temperature measurements are based on an empirical temperature scale defined by the CGPM from time to time.

7.3 Practical temperature scales

The current practical temperature scale is known as the International Temperature Scale of 1990, (ITS-90). The first practical temperature scale known as ITS-27 was defined in 1927.The ITS-27 was revised in 1948 to become the ITS-48, and in 1968 a more comprehensive revision gave rise to the International Practical Temperature Scale of 1968, IPTS-68. The ITS-90 is an improvement of the IPTS-68.

7.4 International temperature scale of 1990, ITS-90

The international temperature scale of 1990 came into operation on January 01, 1990 as the official international temperature scale. Temperatures on the ITS-90 are defined in terms of equilibrium states of pure substances (defining fixed points), interpolating instruments and equations that relate the measured property to ITS–90 temperature.The defining fixed points in the range –38.83 °C to 1084.62 °C are given in Table 7.1

Table 7.1-Defining fixed points of ITS-90

Material	Equilibrium State	Temperature	
		kelvin (K)	Celsius (°C)
Hydrogen	Triple point	13.8033	-259.3467
Hydrogen(orHe)	Vapour pressure	17	-256.15
Hydrogen (or He)	Vapour pressure	20.3	-252.85
Neon	Triple point	24.5561	-248.5939
Oxygen	Triple point	54.3584	-218.7916
Argon	Triple point	83.8058	-189.3442
Mercury(Hg)	Triple point	234.3156	-38.8344
Water (H_2O)	Triple point	273.16	0.01
Gallium (Ga)	Melting point	302.9146	29.7646
Indium(In)	Freezing point	429.7485	156.5985
Tin (Sn)	Freezing point	505.078	231.928
Zinc (Zn)	Freezing point	692.677	419.527
Aluminium (Al)	Freezing point	933.473	660.323
Silver (Ag)	Freezing point	1234.93	961.78
Gold (Au)	Freezing point	1337.33	1064.18
Copper (Cu)	Freezing point	1357.77	1084.62

The most easily realised fixed point is that of the triple point of water, which has been assigned the value of 273.16 K (0.01° C). All the fixed points above this temperature are freezing points except for gallium point, which is defined as a melting point.

A freezing point is the temperature at which a substance changes state from a liquid to a solid. Similarly a melting point is the temperature at which a substance changes state from a solid to liquid. During these transitions the temperature remains constant and a freezing or melting plateau is observed.

The temperature at which solid, liquid and gaseous states of a substance co-exist in dynamic equilibrium is known as a triple point. Thus ice, water and water vapour co- exist in dynamic equilibrium at the triple point of water.

7.4.1 Interpolation instruments

Temperatures at intermediate points in the scale are realised using thermometers known as interpolation instruments. Standard platinum resistance thermometers are designated as the interpolation instruments in the range 13.8033 K (the triple point of hydrogen) to 961.78 °C

(the freezing point of silver). Beyond 961.78 °C the scale is defined in terms of a reference black body radiator.

7.4.2 ITS-90 Reference functions

The ITS-90 defines both the international Kelvin temperatures (T_{90}) and international Celsius temperatures (t_{90}).T_{90} and t_{90} are related by the equation :

$$t_{90}/^{O}C=t_{90}/K - 273.15 \qquad (7.1)$$

The standard platinum resistance thermometer is the ITS-90 interpolation instrument from 13.8 K to 962 °C .The behaviour of a SPRT on ITS-90 is represented by a reference function. There are two ITS-90 reference functions, a twelfth degree polynomial for the temperature range 13.8 K to 273.16 K and a ninth degree polynomial for the temperature range 0 °C to 961.78 °C. Details of these functions are given in Reference xxx.

7.5 Industrial thermometers

A number of different types of thermometers are used in industrial temperature measurements. The main types being :

Thermocouple thermometers

Resistance thermometers

Liquid in glass thermometers

Bimetallic thermometers

Radiation thermometers

Optical pyrometers

7.5.1 Thermocouple thermometers

A thermocouple thermometer consists of a thermocouple sensing element producing an electromotive force (emf) connected to a device capable of measuring the electromotive force (emf) and displaying the result in equivalent temperature units. Such a system is shown in Fig 7.1.

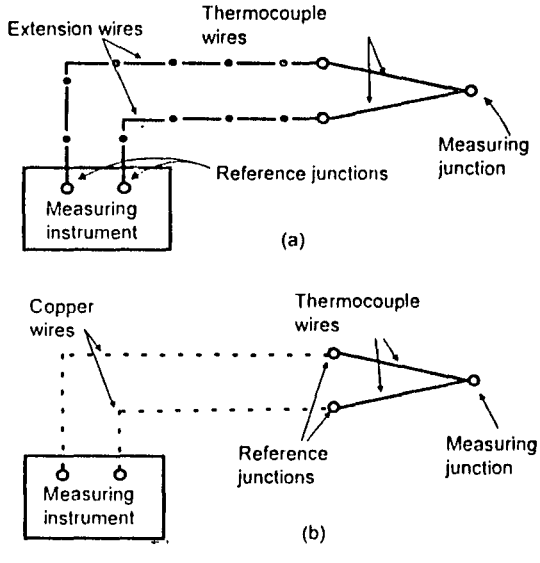


Figure 7.1-**Thermocouple thermometer system**

a) Principle of operation

When a finite conductor is subject to a steady temperature gradient the energy levels (Fermi levels) of the electrons which depend on temperature are different. There are more high

energy electrons in the hotter region and they move towards the cooler region of the conductor. The resulting separation of charges produces a potential difference at the ends of the conductor. This effect was discovered by Seebeck in 1821 and is known as the Seebeck effect. The potential difference produced per unit temperature difference is known as the Seebeck coefficient and is different for different metals.

If the two junctions of a closed circuit formed by joining two dissimilar metals are maintained at different temperatures, an electromotive force (emf)) proportional to the difference of the Seebeck coefficients is produced within the circuit (Fig 7.2). If the temperature of one junction is fixed at some known value, then the temperature of the other junction can be determined by measuring the electromotive force (emf) generated in the circuit.

This is the basic principle of thermoelectric thermometry. The junction with the fixed temperature is known as the *reference junction* and is usually kept at 0 °C (ice point). The other junction is known as the *measuring junction.*

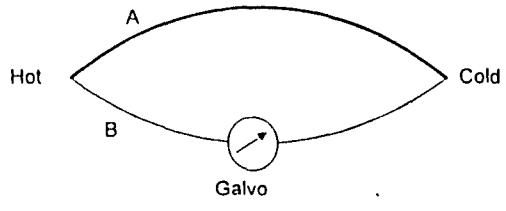


Figure 7.2-Thermoelectric circuit

b) Types & materials

A large number of thermocouple materials have been studied and reported on. The eight types that are used industrially, known as letter designated types have been standardised internationally. Table 7.2 gives the standard types and typical uses for them.

The letter designation of the commonly used thermocouple types was introduced by the Instrument Society of America (ISA) and adopted in 1964 as an American National Standard. (C96.1) .The letter designations identify the reference tables and may be applied to any thermocouple that has a temperature -electromotive force (emf) relationship agreeing within the tolerances specified in the standard. Substantial variations in composition for a given letter type can occur, particularly for types J, K and E.

Table 7.2-Properties of standardised letter designated thermocouples (Source: IEC 60584)

Type	Materials	Allowable environment	Maximum operating temperature, °C	Minimum wire diameter, mm
T	Copper/Copper-nickel alloy	Oxidising, reducing Inert or vacuum	370	1.63
J	Iron/copper-nickel alloy	Oxidising, reducing, inert or vacuum	760	3.25
E	Nickel-chromium alloy/copper-nickel alloy	Oxidising or inert	870	3.25
K	Nickel-chromium alloy/nickel aluminium alloy	Oxidising or inert	1260	3.25
N	Nickel-chromium-silicon alloy /nickel-silicon-magnesium alloy	Oxidising or inert	1260	3.25
R	Platinum-13 % rhodium alloy /platinum	Oxidising or inert	1480	0.51
S	Platinum-10%rhodium alloy /platinum	Oxidising or inert	1480	0.51
B	Platinum-30%rhodium alloy/platinum-6%rhodium alloy	Oxidising or inert	1700	0.51

c) Tolerances

The tolerance of a letter designated thermocouple is defined as the permissible deviation of the electromotive force (emf) generated by it at a specific temperature, from the corresponding value of electromotive force (emf) given in the reference tables, the reference junction being maintained at 0 °C.

Tolerances as given in IEC 60584 are given in Table 7.3. These tolerances apply to new essentially homogeneous thermocouple wire, nominally in the size range 0.25 mm to 3 mm in diameter and used at temperatures not exceeding the maximum temperature given in Table 7.2.

Table 7.3-Tolerances on initial values of electromotive force (emf) Vs temperature of letter designated thermocouples (Source: IEC 60584)

Types	Temp range & Tolerance value	Class1	Class 2	Class 3
Type T	Temp range, °C	-40 to 125	-40 to 133	-67 to +40
	Tolerance value, °C	±0.5	±1	±1
	Temp range, °C	125 to 350	133 to 350	-200 to –67
	Tolerance value, °C	±0.004.t	±0.0075.t	±0.015.t
Type J	Temp range, °C	-40 to +375	-40 to +333	–
	Tolerance value, °C	±1.5	±2.5	–
	Temp range, °C	375 to 750	333 to 750	–
	Tolerance value, °C	±0.004.t	±0.0075.t	–
Type E	Temp range, °C	-40to +375	-40 to 333	-167 to +40
	Tolerance value, °C	±1.5	±2.5	±2.5
	Temp range, °C	375 to 800	333 to 900	-200 to –167
	Tolerance value, °C	±0.004.t	±0.0075.t	±0.015.t
Type K, Type N	Temp range, °C	-40 to +375	-40 to +333	-167 to +40
	Tolerance value, °C	±1.5	±2.5	±2.5
	Temp range, °C	375 to 1000	333 to 1200	-200 to –167
	Tolerance value, °C	±0.004.t	±0.0075.t	±0.015.t
Type R, Type S	Temp range, °C	0 to 1100	0 to 600	–
	Tolerance value, °C	±1	±1.5	–
	Temp range, °C	1100 to 1600	600 to 1600	–
	Tolerance value, °C	± (1+0.003(t-1100)	±0.0025.t	–
Type B	Temp range, °C	–	–	600 to 800
	Tolerance value, °C	–	–	±4
	Temp range, °C	–	600 to 1700	800 to 1700
	Tolerance value, °C	–	±0.0025.t	±0.005.t

t-modulus of temperature in °C

d) Insulation and Sheathing

Individual thermocouple wires are separated from each other by using an insulating material. Different types of insulation and their properties are given in Table 7.4

In addition, to protect the thermocouple from the environment an outer sheath or a protective tube (thermowell) is used. The types of sheathing materials in common use are given in Table 7.5.

One of the most common types in current use, the metal sheathed, and ceramic insulated thermocouple cable provides good electrical and mechanical protection. The sheathing also provides some protection against contamination. However the metal and insulation could affect the thermocouple at high temperatures due to metal migration

The sheathing and end capping processes may give rise to extra strains in the wire and may not be entirely removed by annealing (prolonged heating at a uniform temperature).

Table 7.4-Thermocouple insulation materials

Insulation type	Temperature range, °C	Remarks
Polyvinyl chloride(PVC)	-40 to +105	Resistant to abrasion,moisture,oil and many chemicals.However PVC is attacked by ketones, and esters.
FEP(fluorinated ethylene propylene) Teflon® or Neoflon	-200 to +200	Superior abrasion and moisture resistance.
PTFE Teflon® or Neoflon	-267 to +267	Superior abrasion and moisture resistance.
Kapton(polymide)	-267 to +316	Excellent moisture and abrasion resistance, high dielectric strength. Retains much physical integrity after gamma radiation.
Glass braid	-73 to +482	Glass braid impregnated with silicon varnish has good moisture and abrasion resistance but is destroyed above 400 oF.
High temp glass braid	-73 to + 704	High temperature glass braid impregnated with silicon varnish has good moisture and abrasion resistance. However the impregnation is destroyed above 200°C.

Teflon® is a registered trademark of DuPont, USA.

e) Extension and Compensation leads

In Fig 7.2 the measuring instrument is directly connected between the hot and cold junctions of the thermocouple circuit. However, this is not always practicable as the measuring junction may be at a considerable distance away from the measuring unit (Fig 7.1), and connecting wires have to be used. The same type of material as in the thermocouple should be used for the connecting wires so that extraneous electromotive force (emf) s generated due to dissimilarity of the metals are minimised.

For base metal thermocouples (types E, J, K, T and N) extension wires, of the same material as those of the thermocouple elements in the form of flexible multistranded wire are used. For the more expensive rare metal thermocouples (types R, S & B) the connecting wires in the form of compensation leads made of cheaper materials (copper based alloys), can be used. Compensation leads having a thermoelectric behaviour similar to that of the thermocouple leads over a narrow temperature range, usually less than 50 °C are commercially available.

f) Reference (cold) junction

For very accurate work such as calibration of thermocouples the reference junction is kept in an ice bath. However in most modern thermocouple thermometers cold junction compensation is incorporated. The cold junction is made to remain at a constant temperature by attaching it to a thick copper block (isothermal block) and its temperature is measured with an electric temperature sensor. A silicon sensor is commonly used for the purpose. A correction to the electromotive force (emf) generated between the measuring and cold junctions is calculated using the measured temperature of the cold junction and standard temperature-millivolts tables (or equivalent regression equations). This is usually done by a microprocessor incorporated within the instrument.

Table 7.5-Thermocouple sheath materials

Sheath material	Maximum continuous temperature	Remarks
Refractory oxide, recrystallised, e.g Alumina (Impervious)	1750°C	Good choice for rare metal thermocouples. Good resistance to chemical attack. Mechanically strong but severe thermal shock should be avoided.
Silicon Carbide (Porous)	1500°C	Good level of protection even in severe conditions. Good resistance to reasonable levels of thermal shock. Mechanically strong when thick wall is specified but becomes brittle when aged. Unsuitable for oxidizing atmospheres but resists fluxes.
Impervious Mulite	1600°C	Good choice for rare metal thermocouples under severe conditions. Resists Sulphurous atmospheres. Thermal shock should be avoided.
Mild Steel (cold drawn seamless)	600°C	Good physical protection but prone to rapid corrosion
Inconel 600/800*	1200°C	Nickel-Chromium-Iron alloy which extends the properties of stainless steel 25/20 to higher operating temperature. Excellent in Sulphur free atmospheres; superior corrosion resistance at higher temperatures.
Stainless steel 25/20	1150°C	Resists corrosion even at elevated temperature. Can be used in Sulphurous atmospheres.
Chrome Iron	1100°C	Suitable for very adverse environments. Good mechanical strength. Resists severely corrosive and sulphurous atmospheres.
Nicrobell*	1300°C	Highly stable in vacuum and oxidizing atmospheres. Corrosion resistance generally superior to stainless steels. Can be used in Sulphurous atmospheres at reduced temperatures..

*Trade name

g) Measurement of thermocouple output

The output of a thermocouple is mostly in the millivolt range. Therefore reliable measurement requires a voltmeter with high input impedance or a potentiometer. In calibration laboratories the output electromotive force (emf) is measured using a digital voltmeter or potentiometer. In industrial situations the output is either fed into a digital temperature display or temperature transmitter.

7.5.2 Resistance thermometers

a) Principle of operation

A change in temperature of a resistive element changes its resistance value. This principle is utilised in a resistance thermometer. In the most common type of resistance thermometers, platinum is used as the material of the resistive element. Copper and nickel resistance thermometers are also used in industrial applications.

b) Platinum resistance thermometers

Platinum resistance thermometers are available in two grades, precision grade and industrial grade.

Precision grade platinum resistance thermometers are used as interpolating instruments in the ITS-90 temperature scale and are known as Standard Platinum Resistance Thermometers (SPRTs). These thermometers are of very good stability and precision and are used as secondary standards in national standards laboratories.

SPRT s are available having nominal resistances of 25 ohms and 100 ohms at 0 °C. Some manufacturers have introduced recently, a new type of thermometer of 0.25 ohms resistance and having a temperature range of 0-1000 °C. These thermometers, which are expensive and fragile, are only suitable for use in primary level calibration facilities. However more robust stainless steel sheathed SPRT s are also available.

The industrial grade platinum resistance thermometers are of more robust construction and are widely used for measurement of temperature in industrial situations.

c) Pt-100 resistance thermometers

The class of thermometers known as Pt-100 is widely used for industrial temperature measurements. The requirements of these thermometers are given in IEC Publication 60751.These thermometers have a nominal resistance of 100 Ohms at 0 °C. They come in two main categories, wire wound and film types.

d) Wire wound type

The best wire wound thermometers conform closely to the construction pattern used in working standard platinum resistance thermometers. They are constructed with an alloy comprising of pure platinum alloyed with other platinum group metals to make the temperature co-efficient close to 0.003850 which is the value recommended by the standard IEC 60751.

A bifilar winding is wound around a glass or ceramic bobbin, attached to leads and sealed by a layer of glass. This type is very rugged and can stand high vibration. However this type of construction is subject to strain during temperature cycling and also the resistive element is not directly in contact with air.

In another form of construction a fine coil of platinum wire is led through holes in an alumina tube and attached to more robust leads. The coil is either partially supported or totally supported along its length and the leads are sealed in place with glass or ceramics.

In the partially supported form of construction the wire is wound into a very small coil and inserted into axial holes in high purity alumina rod. A small quantity of glass adhesive is introduced into these holes, which, after firing, firmly secures part of each turn into the alumina. This results in a detector in which the majority of the platinum wire is free to move giving very good long term stability and ability to stand considerable vibration levels (upto 30 g). Fig. 7.3 shows the construction details of a partially supported detector.

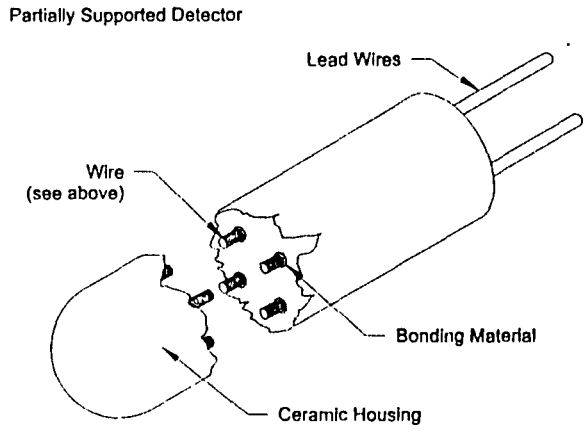


Figure 7.3-Construction details of a partially supported industrial grade platinum resistance detector (Source: Isothermal Technology Ltd.,U.K)

e) Film type

Film type thermometers are constructed using two main techniques. Thick film detectors are made by spreading a glass/platinum paste through a silkscreen mask onto a substrate. Thin film detectors are fabricated by evaporating a metal or alloy onto a substrate, usually alumina in a vacuum chamber.

f) Range

The industrial grade platinum resistance thermometer can be used over the range 0 °C to 850 °C and -200°C to 0 °C. The latter range thermometers have to be sealed to prevent moisture accumulation shorting out the leads.

g) Tolerance

The tolerance of an industrial grade PRT is defined as the maximum allowable deviation expressed in °C from the nominal resistance –temperature relationship. For sensors conforming to IEC 60751 the tolerances are computed from the following equations :

h) Class Tolerance, °C

A $\pm (0.15 + 0.002 \cdot t)$

B $\pm (0.3 + 0.005 \cdot t)$

In these equations t is the modulus of the sensor temperature in °C. Tolerances worked out from the above equations for sensors of 100 Ohms nominal value are given in Table 7.6.For 100 Ohm sensors Class A tolerances are not specified above 650 °C. Also thermometers with only two connecting wires are not categorised in Class A.

Table 7.6-Tolerances for industrial grade platinum resistance sensors (Source: IEC60751)

Temperature	Tolerance			
	Class A		Class B	
°C	± °C	± Ω	± °C	± Ω
-200	0.55	0.24	1.3	0.56
-100	0.35	0.14	0.8	0.32
0	0.15	0.06	0.3	0.12
100	0.35	0.13	0.8	0.30
200	0.55	0.20	1.3	0.48
300	0.75	0.27	1.8	0.64
400	0.95	0.33	2.3	0.79
500	1.15	0.38	2.8	0.93
600	1.35	0.43	3.3	1.06
650	1.45	0.46	3.6	1.13
700	-	-	3.8	1.17
800	-	-	4.3	1.28
850	-	-	4.6	1.34

Terminals

PRT sensors are manufactured with two, three or four terminals. The terminal color coding and sensor identification system given in IEC 60751 are given in Fig 7.4

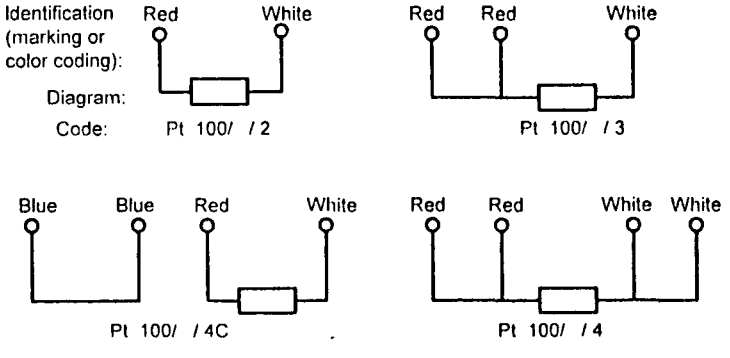


Figure 7.4-Terminal configurations and colour coding of industrial grade platinum resistance sensors (Source: IEC 60751)

7.5.3 Liquid in glass thermometers

a) Principle of operation

Liquid in glass thermometers make use of the expansion of a liquid in a glass capillary tube to sense the temperature of the bulb. The temperature is obtained by reading the position of the meniscus from a scale engraved on the capillary stem.

b) Types

Liquid in glass thermometers belong to several different types manufactured to conform to a number of national and international standards. International organisation for standardization

(ISO), British (BS),American Society for Testing & Materials (ASTM) , and Institute of Petroleum (IP) are the most common standard specifications.

Thermometers filled with mercury are the most common type. Other liquids e.g. alcohols are sometimes used instead of mercury to extend the range.

Industrial type thermometers are usually encased in metallic enclosures.

c) Range

Mercury in glass thermometers can be obtained having a measuring range of –20 °C to about 600 °C. The finest resolution obtainable is 0.01 °C over limited temperature ranges. Spirit filled thermometers can be used down to –200 °C.

d) Construction

A liquid in glass thermometer consists of a glass bulb filled with the liquid (mercury or spirit) joined to a capillary tube having a uniform bore and sealed at the end. In mercury in glass thermometers the space above mercury is usually filled with nitrogen to minimise column breaks and prevent the mercury from boiling over at higher temperatures. Other essential features of good quality thermometers are :

Glass

The glass used in the manufacture of the thermometer must be able to withstand the maximum temperature and should have a small coefficient of expansion. Usually the glass is identified by one or two coloured lines on the length of the bulb, or by a coded inscription on the stem.

Properties of glasses suitable for construction of thermometers are given in ISO 4795 and a number of national standards.

Bore

The diameter of the bore should be uniform without reductions or constrictions.

Contraction chamber

A contraction chamber (an enlargement of the bore) is normally provided if the thermometer has two scale segments e.g. one near 0 °C and another say between 50 °C –100 °C.

Expansion volume

An expansion volume may also be incorporated at the top of the bore. This may be a tapered enlargement or simply a suitable extension of the capillary above the highest scale line.

Graduations

Scale lines should be clearly and durably marked, evenly spaced, and of uniform thickness not exceeding one fifth of the interval between consecutive lines.

Immersion depth

The reading obtained from a liquid in glass thermometer depends to some extent on the mean temperature of the emergent liquid column. Three conditions of immersion are used:

a) **Total immersion thermometer**- the thermometer is immersed to within a few mm of the meniscus when a reading is taken.
b) **Partial immersion thermometer** – the thermometer is immersed only to a designated mark on the stem.
c) **Complete immersion thermometer** – requires the entire body of the thermometer to be immersed.

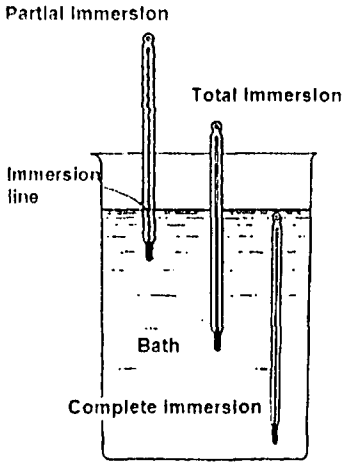


Figure 7.5-Types of Immersion of liquid in glass thermometers

e) Stability and Accuracy

The secular change and temporary depression of zero are the main effects contributing to the instability of liquid in glass thermometers. However well annealed and calibrated thermometers are usually accurate to about 0.2-0.5scale divisions. Accuracies of ASTM thermometers are specified in ASTM E1 and those of reference quality thermometers in British Standard 1900. In general a good practical guide for the scale error of a thermometer is its resolution. A thermometer whose scale error is more than one resolution should be discarded.

7.5.4 Bimetallic thermometers

a) Principle of operation

The difference in the thermal expansion of two metals is utilised in the operation of a bimetallic thermometer. The bimetallic sensor consists of a strip of composite material wound in the form of a helix. The composite material consists of dissimilar metals fused together to form a laminate. The difference in thermal expansion of the two metals produces a change in curvature of the strip with changes in temperature. The helical construction of the bimetallic strip translates this change of curvature to a rotary motion of a shaft.

b) Construction

A bimetallic thermometer consists of an indicating or recording device, a sensing element known as bimetallic thermometer bulb and means for connecting the two, Fig 7.7. The sensing element is enclosed in a metallic protective case.

The rotation of the bimetallic sensing element is transmitted to a shaft and attached pointer. A scale graduated in temperature units enables the pointer rotation to be read as temperature values.

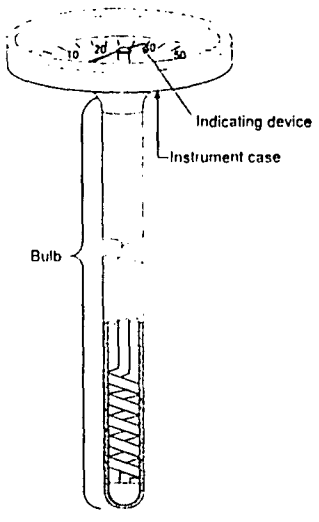


Figure 7.6-Construction of a bimetallic thermometer

c) Types

Basically there are two types of bimetallic thermometers, industrial type and laboratory or test type.

Industrial type thermometers are generally available with 25 mm (½ in) or 75 mm (¾ in) standard pipe thread connections. The bulb diameter varies from 3 mm to 10 mm. Bulb lengths from 60 mm to 1.5 m are available.

Laboratory or test type thermometers are of higher accuracy than the industrial type.

Both types are available as straight and angled thermometers. Thermometers are also available with extra pointers that indicate maximum and minimum temperatures. In some thermometers, the stem is filled with silicone oil for providing shock and vibration protection.

d) Range

Bimetallic thermometers are available in the temperature range -100 °C to 540 °C. However they are not suitable for continuous operation above 400 °C.

e) Accuracy

The accuracy of bimetallic thermometers depends on a number of factors, the design environment, immersion, thermal stability of the bimetal element etc. Generally thermometers having an accuracy of ±1 per cent of reading are available.

7.5.5 Radiation thermometers

a) Principle of operation

All objects with a temperature above absolute zero emits radiant energy from their surface. As the temperature of the object increases more and more energy is emitted eventually emitting visible energy at around 650 °C. The relationship between wavelength of the emitted radiation and spectral radiance is shown in Fig 7.8.

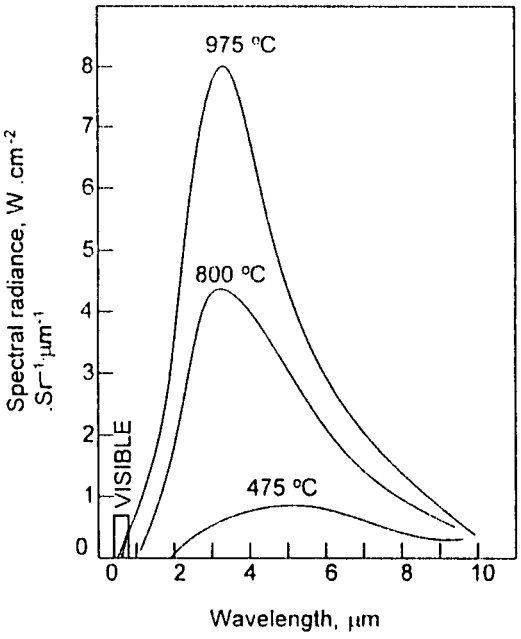


Figure 7.7-Blackbody radiation characteristics

Fig 7.7 illustrates two fundamental physical principles :

a) The amount of thermal energy possessed by an object increases as the temperature of the object increases. The area under the curve represents this.
b) As the temperature increases, more energy is emitted at progressively shorter wavelengths until, at around 650 oC, the radiant energy is in the form of visible light.

In a radiation thermometer these basic principles are utilised to measure temperature. Infra red energy is focused by a suitable lens onto a radiation detector. The electrical signal produced by the detector, which is proportional to the incoming energy, is transmitted to a recording or indicating device.

The types of radiation detectors used today and their characteristics are given in Table 7.7

Table 7.7-Types of radiation detectors and their characteristics (Source: Institute of Measurement & Control, U.K)

Detector	Wavelength, µm	Temperature range, °C	Response speed , ms
Silicon	0.7 to 1.1	400 to 4000	10
Lead sulphide	2.0 to 2.6	100 to 1400	10
Pyroelectric	3.4 to 14	0 to 1500	100
Thermopile	1 to 14	-150 to + 500	100

The characteristics shown reinforce a basic rule of thumb:

short wavelength =high temp ; long wavelength = low temperature.

b) Emissivity

Emissivity is a parameter, which characterises the amount of energy an object emits from its surface. It is defined as :

$$\varepsilon_\lambda = \frac{\text{Spectral radiance of object at wavelength } \lambda}{\text{Spectral radiance of blackbody at wavelength } \lambda}$$

ε_λ - Emissivity of object surface at wavelength λ

(7.3)

In practice all objects emit less than 100 percent of their energy, so emissivity values are always less than 1.00.The only object that emits all of its thermal energy is a black body. Black body radiators are specialist designs used as the standard for calibrating radiation thermometers.

The accuracy of the values displayed by a radiation thermometer depends on the emissivity of the object being measured. The emissivity - wavelength relationship is non-linear for a majority of objects. The normal trend is for emissivity to be higher at shorter wavelengths than at longer wavelengths. Also as the temperature of an object changes its emissivity can change.

Although this causes problems with measurement accuracy, the expected error can be quantified as a function of wavelength and temperature. Table 7.8 indicates the error in °C, for 1 % change in emissivity, related to temperature and wavelength of most commercially available radiation thermometers.

Table 7.8 -Change in temperature reading caused by one percent change in emissivity

Wavelength µm / Temperature	0.65	0.9	1.6	2.3	3.4	5.0	10.6
°C							
100	0.06	0.08	0.15	0.22	0.33	0.49	1.00
500	0.27	0.37	0.68	0.96	1.40	2.10	3.60
1000	0.74	1.00	1.80	2.60	3.70	5.10	7.80
1600	1.60	2.20	4.0	5.50	7.50	9.60	13.00

The obvious fact from Table 7.8 is that using the shortest possible wavelength will minimise the effects of emissivity variation on the temperature being measured.

c) Types

A large variety of radiation thermometers are available, with variations in temperature measurement range, detector type, operating wavelength and lens material. It is impossible to summarise all the options available. Table 7.9 shows a broad overview of types available related to their possible uses in industry.

Table 7.9-Types of radiation thermometers and their possible uses in industry

Wavelength μm	Temperature range °C	Detector	Lens	Primary areas of application
0.65	700-3500	Silicon	Crown glass	Molten steel and molten glass
0.7-1.08	550-3000	Silicon	Crown glass	Iron, steel foundries and semiconductor
0.9-1.08	300.2800	Silicon	Crown glass	Silicon wafers and high temperature steel requiring wide ranges
0.7-1.08 1.08 two color	700-3500	Silicon	Special lens	High temperature applications in dusty or smoky atmospheres or small targets .e.g. kilns ,vacuum furnaces
1.64	250-1100	Germanium	Crown glass	Best choice for non-ferrous metals
2-2.6	80-800	Lead sulphide	Crown glass	Low temperature metals and small targets
3.4	0-800	Indium arsenide	Calcium fluoride	Thin film organic plastics, paints, waxes, oils
3.9	300-1300	Thermopile	Calcium fluoride	Furnace walls of glass melters
4.8-5.3	50-2500	Pyroelectric thermopile	Zinc sulphide	Glass surface temperature for sealing, bending, annealing, tempering and forming
7.9	20-400	Pyroelectric thermopile	Zinc sulphide	Thin films of polyester and fluorocarbons, thin glass and ceramics
8-14	-50-500	Pyroelectric thermopile	Zinc sulphide	General purpose low temperature, paper, food textiles.

d) Ratio thermometers

A ratio thermometer consists of two detectors working at two different wavelengths. For this reason they are also known as two color thermometers. The ratio of the outputs of the two detectors (V_1/V_2) is given approximately by the following equation :

$$\frac{V_1}{V_2} = f(T)\frac{\varepsilon_1}{\varepsilon_2} \times \frac{\lambda_1}{\lambda_2} \qquad (7.4)$$

where T is the target temperature and ε_1 and ε_2 are emisivities of the target at wavelengths λ_1 and λ_2.Since the wavelength ratio λ_1/λ_2 is a constant and the emissivity ratio $\varepsilon_1/\varepsilon_2$ is nearly equal to 1 the ratio of the outputs can be written as:

$$\frac{V_1}{V_2} = k \times f(T) \qquad (7.5)$$

which shows that the ratio of the outputs is proportional to the target temperature. The reading of a ratio thermometer is therefore largely unaffected by attenuation of the radiation by dust, smoke or steam, providing the two detectors both received the same amount of attenuation. For this reason ratio thermometers are an excellent choice for situations where the target is obscured by smoke, steam or dust or the target area of the thermometer is not completely filled .i.e. the target is small or a thin wire.

However ratio thermometers are also affected by the variation of emissivity of the target. The effect on temperature due to variation of emissivity during a process is something that can only be minimised not eradicated.

e) Portable instruments

Portable radiation thermometers have been available since the early 1970 s. The typical features of a portable radiation thermometer are variable focus, through the lens sighting, with definition of the target area to be measured by a reticle in the viewfinder. This is essential to ensure accurate sighting of the target area. In most types the target temperature is displayed in the view finder. Although a variety of models are available two particular model specifications are common. These are given in Table 7.10:

Table 7.10-- Typical specifications of portable radiation thermometers

Detector	Wavelength	Temperature Range	Field of view
Silicon	0.7 to 1.0 μm	600 °C to 3000 °C	Distance to target/100
Thermopile	8 to 14 μm	-50 °C to +1000 °C	Distance to target /40

The high temperature instrument is particularly used in the steel, glass, ceramics and metal processing industries, while the lower temperature instrument is used in a wide variety of process industries such as food, plastics and paper.

f) Fixed instruments

A fixed installation radiation thermometer is used to monitor a single position, and feed its output either to a remote temperature display, or to a process control system.

g) Scanning instruments

A scanning radiation thermometer is used to measure the temperature profile of a broad target such as a strip of steel or sheet of glass. A line scanner can be used to measure the temperature of a moving target along a line perpendicular to the direction of travel. If a number of such crosswise profiles are obtained it is possible to generate a two dimensional thermal map of the object being measured. The outputs of the scanners are either analogue 4 to 20 mA or RS 485 signals, which can be interfaced with plant control systems.

7.5.6 Optical pyrometer

Basically there are three types of optical pyrometer:

a) Disappearing filament type

b) Constant radiance disappearing filament type

c) Automatic pyrometer

a) Disappearing filament pyrometer

The schematic of a disappearing filament type pyrometer is shown in Figure 7.8.

An objective lens focuses a real image of the target in the plane a standard filament lamp. Both the image and the filament are magnified by a microscope lens and an ocular lens. The eye piece is focused to obtain a sharp image of the lamp filament and then the target image is focused by adjusting thy objective lens.

The red filter between the microscope lens and the lamp provides approximately monochromatic light to the observer. In taking a reading the current through the lamp filament is adjusted until the filament is of the same luminance as the image of the target. The outline of the filament in the field of view disappears when the current is properly adjusted. The current through the lamp is measured using an ammeter and indicated on a display in units of temperature.

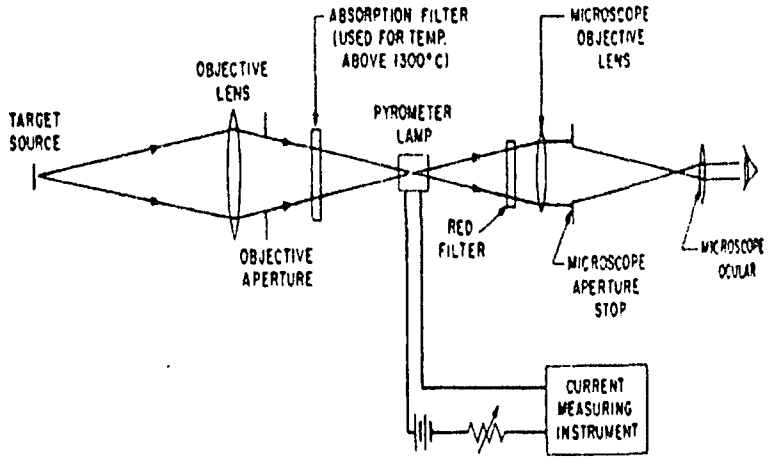


Figure 7.8-Disappearing filament type pyrometer

Standardised absorption glass filters are interposed between the target and the lamp, permitting a wide range of temperature to be measured, without using high filament temperatures. Optical pyrometers of this type are available covering the temperature range 700 °C to 10000 °C.

b) Constant Radiance disappearing filament pyrometer

The schematic of a constant radiance pyrometer is given in Figure 7.9 A circular spot (test spot) on one face of a prism is illuminated using a standard filament lamp. The lamp is operated at a constant preset radiance. (If necessary this could be adjusted using the rheostat and the ammeter). The image of the target is focused on to the bottom face of the prism (test spot). The optical wedge is a gray filter whose transmittance varies as a function of angular rotation. The wedge is rotated to adjust the fraction of radiation transmitted until the target image and the test spot image have the same radiance, at which point the test spot image of the prism disappears in the field of view.

The angular position of the wedge may then be taken as a measure of the target radiance temperature, which is indicated directly on a scale attached to the wedge.

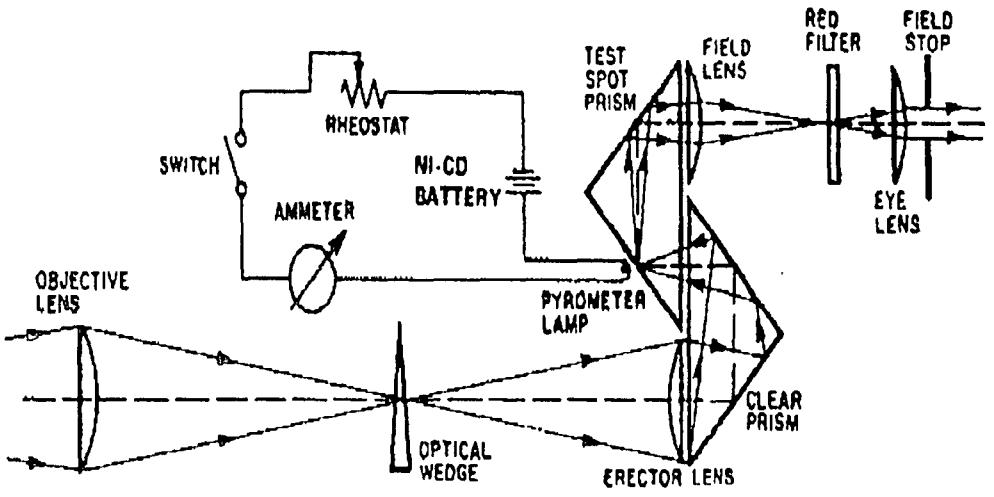


Figure 7.9-Constant radiance disappearing filament pyrometer

c) Automatic optical pyrometer

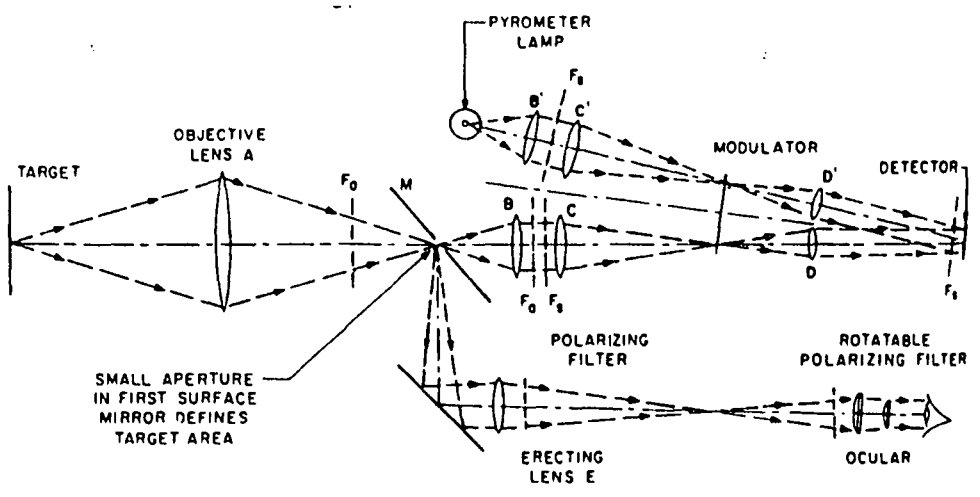


Figure 7.10-Automatic pyrometer

The essential elements of an automatic optical pyrometer (also known as self balancing variable radiance comparison lamp type) are shown in Figure 7.10. Operation of the instrument is similar to that of the disappearing filament optical pyrometer. However the detection of radiation is by a photo detector (usually a photomultiplier tube) and the lamp current is adjusted by electronic null balancing system. The spectral bandwidth employed is usually narrower than in the disappearing filament type.

Radiation from the target is focused on a small aperture in the mirror M. The portion that does not go through the aperture is focused by lenses B and C at the plane of the modulator, after which the image of the lens C is focused on the detector. Radiation from the pyrometer lamp filament is treated in the same manner as radiation passing through the mirror aperture. The modulator allows the detector to receive radiation alternately from the pyrometer lamp and from the detector, but not from both at the same time. An interference filter F_s limits the spectral bandwidth and peak wavelength of radiation arriving at the detector. F_s may be located between lenses B and C and between B' and C' .There are also two alternative locations for the absorbing glass (range changing) filters F_a, one between the lenses B and C and the other between objective lens A and the aperture mirror M.

8 Electrical standards

8.1 Introduction

This chapter outlines the primary, secondary and working standards for voltage, current, resistance, capacitance and inductance. General guidelines for calibration of secondary standards, working standards and test instruments are given in Chapter 15.

8.2 Primary standards

8.2.1 Current balance

The current balance is the primary standard for the realisation of the ampere. A current balance uses the principle enunciated in the definition of the ampere, though in a more practical way. Instead of using long straight conductors, two circular coils are used. One coil is fixed and the other is mounted at the end of a balance arm. The force generated between these coils when a constant current is passed through them is counter balanced by known weights placed on the other arm of the balance. A schematic of the current balance is shown in Figure 8.1.

The uncertainty of realization of the ampere using a current balance is about 15 parts per million (ppm). Due to the difficulty of realization of the ampere using a current balance and the availability of primary standards for the volt and the ohm , in many local and national laboratories it is derived from the ratio of volt and the ohm, using Ohm's law :

$$1\ \text{ampere} = \frac{1\text{volt}}{1\text{ohm}}$$

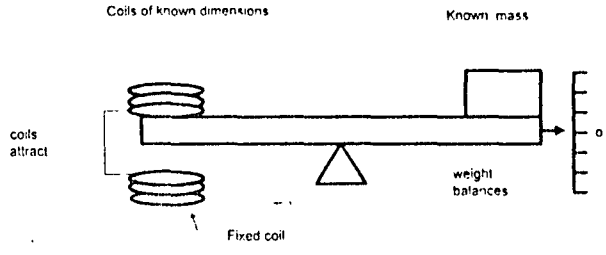


Figure 8.1-Current balance

8.2.2 Josephson standard

Brian Josephson working at the then National Bureau of Standards (NBS) discovered the Josephson effect in 1962.A Josephson junction consists of two superconductors, separated by a thin oxide insulating barrier. When a DC current biased junction is irradiated with a microwave source a DC voltage proportional to the frequency of the microwave source is produced across the junction.

A series of constant dc voltages appears across the junction due to quantum mechanical tunneling of an ac current through the junction. The dc voltage steps are given by the equation :

$$V = \frac{fnh}{2e} = \frac{fn}{K_j}$$

Where :

f - frequency of the ac current,

n - step number,

h - Planck's constant and

e - electronic charge value.

K_j is known as the Josephson constant and has an assigned value of 483 597.9 GHz/ V.

The junction has to be maintained at a temperature below 4.2 kelvin and is located in a dewar containing liquid helium. The voltage produced by a single junction is of the order of 10 mV. Present day Josephson standards consist of arrays of junctions connected in series producing as much as 10 V dc output, Figure 8.2. Recent experiments have shown that the dc voltage developed by Josephson junctions irradiated by a common source of microwaves agrees to within 3 parts in 10^{19}.

Researchers working at the National Institute of Standards & Technology (NIST) have described a compact, transportable and fully automated Josephson standard recently. The uncertainty of realising the volt using this standard is reported to be 1 part in 10^9 at 95 % confidence level.

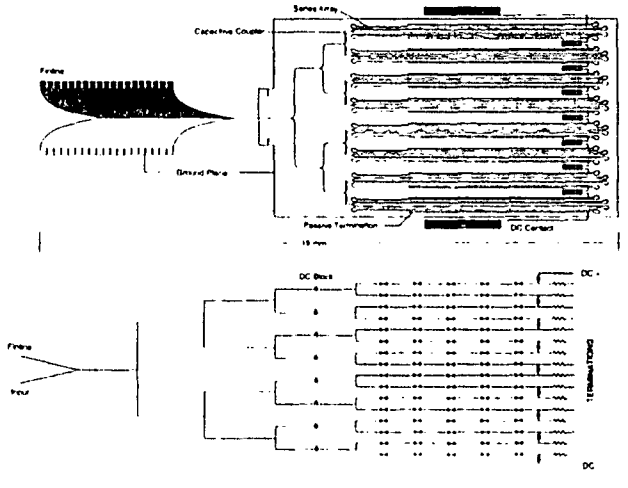


Figure 8.2-Josephson array (Source: Fluke Corp.,USA)

8.2.3 Quantised Hall Resistance Standard

The quantised Hall resistance standard is based on the Quantum Hall Effect (QHE). Klaus Von Klitzing observed the Quantum Hall Effect in 1980 in high quality silicon MOSFETs (Metal Oxide Semi conductor Field Effect Transistors). Subsequent experiments in collaboration with the Physikalisch Technische Bundesanstalt (PTB) in Germany and workers in several other national laboratories confirmed that the Quantum Hall Effect could be used to construct an international resistance standard.

A planar MOSFET transistor constructed to constrain a current of electrons within a thin layer is the main component of a QHE device. The schematic of a simplified QHE device is shown in Figure 8.3

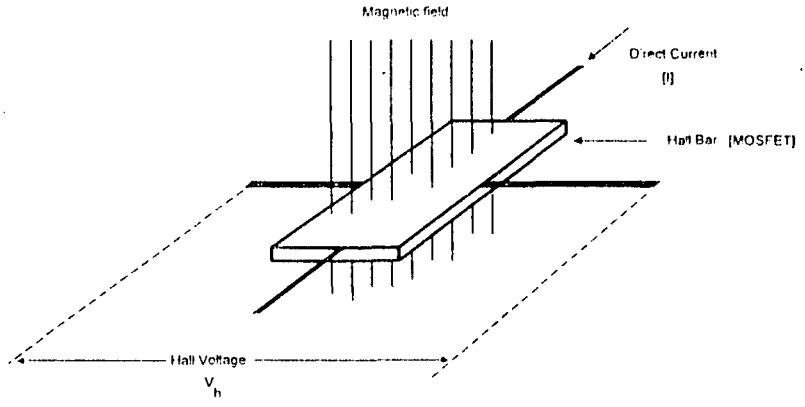


Figure 8.3-Principle of Quantum Hall Effect device

The planar transistor is operated in a cryogenic environment at a temperature of less than 4.2 kelvin, typically in the range of 1 to 2 kelvin. A magnetic field of several tesla is applied perpendicular to the plane of the sample. A direct current is applied along the longitudinal axis of the device and the Hall voltage generated perpendicular to both the magnetic field and the flow of current is measured.

At a constant drive current and as the magnetic field is varied, the Hall voltage is observed as steps due to the quantised action of the electrons, Figure 8.4. Thus small variations in the magnetic field have no effect on the amplitude of the Hall voltage.

The Hall voltage and the Hall resistance are given by :

$V_h = R_{k\text{-}90}\, I/n$

$R_h = V_h/I = R_{k\text{-}90}/n$

where :

V_h – Hall voltage

$R_{k\text{-}90}$ - assigned value of von Klitzing constant

R_h – Hall resistance

n – an integer representing the plateau where the value of R_h is measured

The recommended international value of Von Klitzing constant is 25 812.807 ohms exactly.

Portable Hall resistance standards are also becoming available. A modular and portable standard has been recently reported by researchers of the Institute for National measurement Standards of the National Research Council of Canada.

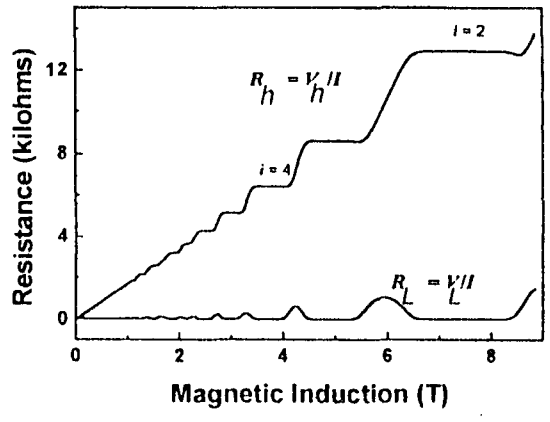


Figure 8.4-Hall voltage steps (Source : National Research Council, Canada)

8.2.4 Calculable Capacitor

The SI unit of capacitance, the farad, is realised by using a Thompson-Lampard calculable capacitor. The calculable capacitor is a linear device known as a cylindrical cross-capacitor. The capacitance per unit length of a cross capacitor can be computed with great precision. A simplified diagram of a cross capacitor is shown in Figure 8.5.

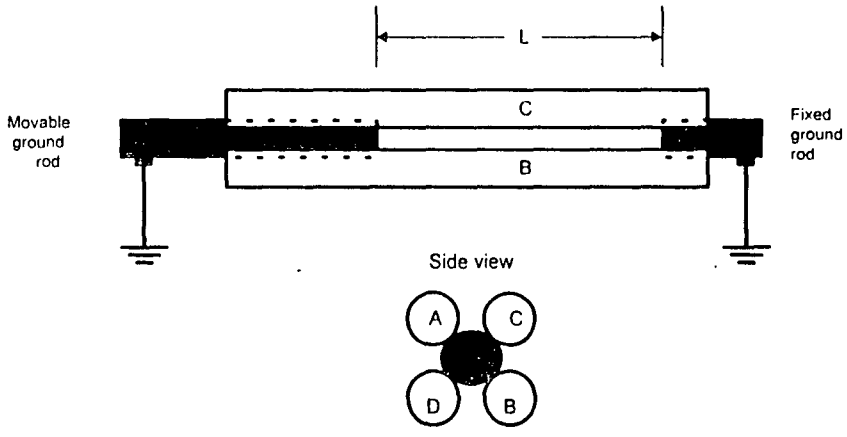


Figure 8.5-Calculable capacitor

In this simplified diagram four bars of circular cross section are placed so that they are at the vertices of a rectangle when viewed end on. The four parallel bars are enclosed in an electrostatic shield. The two diagonally opposite sets of bars each constitute one capacitor.

If the capacitance of the two sets of opposite bars are designated C_1 and C_2, then according to Lampard the mean capacitance $\overline{C}$ is given by

and

$$\overline{C} = \left(\frac{C_1 + C_2}{2}\right)$$

$$\overline{C} = \varepsilon_o L\left[\frac{\ln 2}{\pi}\right]\left[1 + 0.087\left(\frac{(C_2 - C_1)}{\overline{C}}\right)^2\right] + \text{fourth order and higher order terms}$$

where,

$\varepsilon_0 = 1/\mu_0 c^2$

L - length of bars in meters

μ_0= permeability of vacuum

c = speed of light in vacuum

if $C_1 = C_2 = C$ then $C = \varepsilon_o L(\ln 2) / \pi$

Usually the forth and higher order terms can be neglected and the capacitance is approximately 2 pF/m.

However errors arise due to distortion of the electrical field near the ends of the bars. A number of techniques such as movable ground rods are utilised to overcome these difficulties.

8.3 Secondary standards

8.3.1 Standard cells

A bank of saturated Weston cadmium cells had been the dc voltage standard maintained by standards laboratories for a number of years. The saturated cell when carefully used exhibits good voltage stability and long useful life.

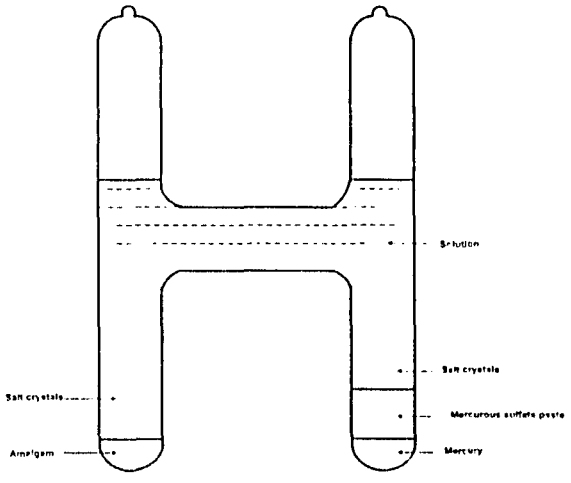


Figure 8.6-Weston cell

The nominal output voltage of a saturated cell is 1.0183 volts at 20 °C. Individual cells may differ from the nominal by tens of microvolts. The saturated cell has a relatively large temperature co-efficient approximately – 40 ppm /°C at 20 °C and therefore has to be kept in a constant temperature bath or oven to maintain a stable voltage.

Standard cell enclosures available commercially usually contain four cells and operate at about 30 °C. Substantial hysteresis is displayed by a cell if its temperature is changed and then returned to normal. Following a change in temperature a cell will either return to its previous value or to a new value. However the stabilisation period to reach within 0.5 ppm of its previous value can be as much as 90 days. Shock or vibration, tripping, gas bubble formation at the electrodes or current flow into or out of the cell may also cause a cell to drift appreciably for extended periods of time.

8.3.2 Maintenance of Standard Cells

Standard cells can exhibit unpredictable drifts or shifts in their output voltage. Due to this reason a number of 4 cell enclosures constituting a bank is used to maintain a voltage standard. At least three four cell enclosures (12 cells) are needed for a reliable voltage standard. The voltage outputs of individual cells are intercompared regularly to determine their deviations from the mean value of the bank with the measurement results plotted on control charts. This arrangement also allows one (or two) enclosures of the bank to be used as a transfer standard to maintain traceability with a national or international laboratory.

The comparative measurements of the cell voltages are made by connecting two cells together in series-opposition, negative terminals connected together, and measuring the difference with a potentiometer or high resistance microvoltmeter. Test protocols, which make it possible to obtain the desired information with a minimum number of measurements, are given in NBS Technical Note 430.

Standard cells are very susceptible to damage due to excessive current flow into or out of the cells. Therefore it is extremely important to avoid current flow into or out of the cells. Currents as low as 10^{-15} amperes, if sustained for several minutes can cause a change in value for which long recovery times are required.

8.3.3 Solid state DC voltage standards

Solid state DC voltage standards are widely used today in standards laboratories. These standards have low temperature coefficients, are able to source and sink current without damage and are mechanically robust. They also have higher output voltages (10 V nominal) that minimize the effects of thermal emf s in connecting leads.

There are basically two types of DC voltage standards in use today; *Reference Amplifier Type* and *Discrete Zener Diode Type.*

a) Reference Amplifier Type

A reference amplifier is an integrated circuit consisting of a Zener diode and a transistor and is illustrated in Figure. 8.7.

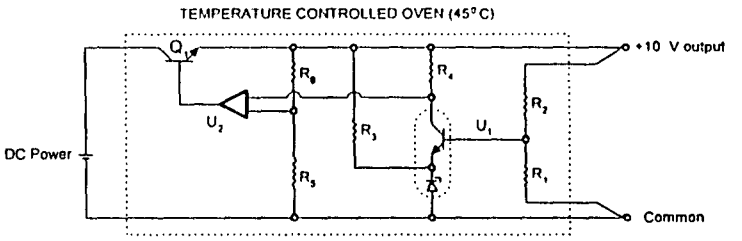


Figure 8.7-Reference amplifier (Source: Fluke Corp., U.S.A)

There are two advantages of using a reference amplifier. The current in the Zener diode can be set independent of the transistor's base current. This allows the amplifier's collector current to be adjusted so that the temperature coefficient of the output is near zero, over a narrow temperature range. Also the reference amplifier's integral transistor allows it to be used in association with a high gain, negative feed back amplifier to provide a regulated output at a higher reference voltage.

b) Discrete Zener Diode Type

A reverse biased diode known as the Zener diode has been in use as a voltage regulator from the advent of solid state devices in the 1950 s.

Early Zener diodes were not very stable and had relatively high noise levels. Today's improved zener diodes are as stable as saturated standard cells. They are also mechanically robust ,unaffected by reasonable levels of shock and vibration and relatively stable to extreme temperature variations.

Figure. 8.8 shows a Zener diode combined with a forward biased diode to achieve near zero temperature co-efficient. In this arrangement the temperature coefficient of the Zener (2 mV/°C), which is positive, is compensated by the nearly equal negative temperature coefficient of the forward biased diode (-2 mV/ °C) to yield a device having a near zero temperature coefficient.

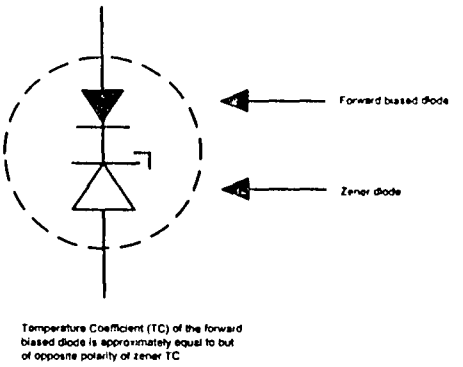


Figure 8.8-Discrete Zener standard (Source: Fluke Corp., USA)

The typical operating voltage of a zener reference diode is between 6.2 V and 6.3 V. However, 10 V, or multiples of 10 V, are the preferred values for the standards laboratory. Most solid-state voltage references used in the laboratory are designed to deliver 10 V, or both 10 V and 1.018 V. These higher voltages are obtained by feeding the 6.2 V Zener reference voltage to a regulated precision 10 V power supply. Isolation for the Zener reference as well as high current capability is provided by the power supply amplifier. In addition current limiting for accidental short circuits are also provided in this arrangement.

The main disadvantage of the discrete amplifier is uncertinties arising from offset drift and noise in the amplifier ,drift in the voltage divider and drift in the output adjustment control adding to the drift in the Zener reference voltage. If the standard has 1 V or 1.018 V outputs obtained by dividing the 10 V output then these will be subject to additional uncertainties arising from the drift in the resistive voltage dividers.

8.3.4 Maintenance of Solid-State voltage Standards

A solid-state voltage standard should always be maintained under power as they may exhibit a small change in output when power is removed and reapplied. This is especially important when solid state references are shipped.

a) Stability of Output With Time

The stability of the 10 V output of a solid state standard is about 0.5 ppm/year. Unlike in the case of standard cells where at least 12 cells are needed to maintain a reliable standard, about four solid state standards are sufficient to maintain a voltage standard. The cells of a bank are intercompared regularly using a high impedance digital voltmeter or a potentiometer. Many laboratories have automated systems using a computer, a thermal scanner and digital voltmeter interconnected using the IEEE 488 interface bus.

Such automated systems enable the intercomparisons of cells on a regular basis (say every two weeks) to determine their drift characteristics. Linear regression and trend fitting techniques are often used to predict the output at a future time. Calibration and drift characterization of solid state voltage standards are described in Chapter 14.

8.3.5 AC- DC transfer standard

An AC-DC transfer standard is used to transfer DC voltages and currents to AC quantities or vice versa. A number of different models of AC-DC transfer standards are in use today.

The older standards based on vacuum thermocouple principles were developed from work done at NBS (presently NIST) in the 1950 s. Most of the current types of AC-DC standards use a solid state device known as RMS sensor introduced in 1974.

a) Vacuum thermocouple based standard

A vacuum thermocouple based standard uses a thermal element which works on the principle of heat generated in a resistance sensed by a thermocouple attached to it. Since the heat generated in a resistive element is only dependent on the mean current passed through it, the root mean square (RMS) value of an alternating current can be made equal to the value of a direct current passed through the element.

The main disadvantage of a single thermocouple is that its output is only a few millivolts (typically 5-10 millivolts). The other problems are their long thermal time constant and direct voltage reversal error. In later years the introduction of multi junction thermal elements giving outputs of the order of 100 millivolts overcame the problem of low voltage output. However the long thermal time constant, direct voltage reversal error and poor frequency response (above 100 kHz) were not entirely overcome.

b) RMS sensor based standard

The original RMS sensor introduced in 1974 was a monolithic device having a transistor and a diffused resistor on a silicon substrate. Power dissipated in the resistor is detected by the

transistor through the temperature sensitivity of the base emitter junction voltage, Figure 8.10.

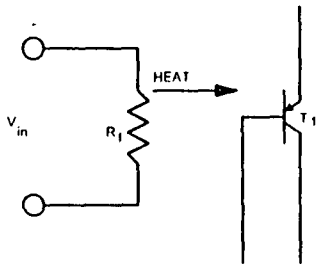


Figure 8.10-Thermal sensor (Source: Fluke Corp., U.S.A)

This device overcame the major disadvantage of the thermocouple or multijunction thermal element, namely the long thermal time constant. However this sensor had a direct voltage reversal error as large as, if not larger than the single junction thermocouple.

These problems were overcome by constructing the RMS sensor as a differential pair using two resistor transistor combinations, Figure 8.11. The application of an input voltage to R_1 causes the temperature of the base emitter junction of T_1 to change. This causes a change in base-emitter voltage (V_{be}) of T1 which in turn controls the collector voltage. The differential amplifier A compares the collector voltage of T_1 and T_2. By driving a current through R_2 the base-emitter voltage of T_2 is changed causing a change in the collector voltage. A balance occurs when the collector voltages of T_1 and T_2 are equal. When this happens the input voltage V_{in} of any waveform is approximately equal to the direct voltage at V_{out}.

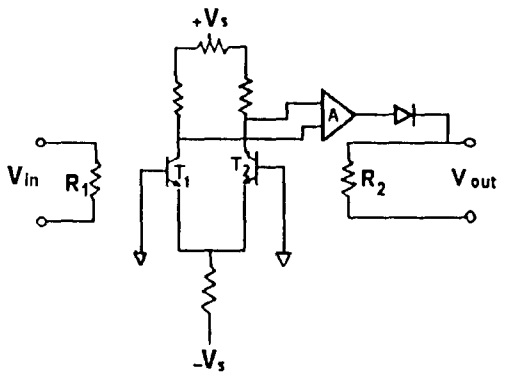


Figure 8.11-Differential pair RMS sensor (Source: Fluke Corp., U.S.A)

8.3.6 Resistance standards

a) Thomas one ohm standard

The Thomas type one ohm standard is a highly stable wire wound resistance standard. The resistance element is contained in a hermetically sealed, double walled metal container. The temperature coefficient of resistance of these resistors is relatively high and therefore they have to be maintained in a temperature controlled oil bath.

The Thomas type one ohm resistance standard is widely used as a secondary reference standard for resistance in many standards laboratories. The value of one ohm standards is transferred to higher valued standards using bridge comparison methods.

The drift of a well maintained Thomas type resistor is of the order of 0.02 ppm per year.

b) CSIRO one ohm standard

More recently, one ohm type standard resistors having superior characteristics to those of Thomas type, especially in respect of temperature and pressure coefficients have been developed by the Commonwealth Science and Industrial Research Organisation (CSIRO) of Australia.

The resistive element is a coil of Evanohm wire annealed at 980 ^{o}C. Further heat treatments at lower temperature are used to obtain a very small temperature coefficient ($1x10^{-6}$ / K or lower at 20 ^{o}C) at ambient temperatures. The heat-treated coil is mounted in a special support and is unsealed. The pressure co-efficient is negligible and long term stability, a few parts in 10^{8} per year.

c) Reichsanstalt Artifact Standard

Reichsanstalt design is often used for low valued standard resistors, from 0.001 ohms to 0.1 ohms which are subjected to high current in use. In this design the resistance wire is wound on a metal tube, which is enclosed in a perforated container. When immersed in a temperature controlled oil bath, the perforations allow free circulation of oil over the resistance element, thereby aiding in cooling of the resistor, particularly when high test currents are used.

d) Rosa Artifact Standard

A design proposed by Rosa is frequently used for construction of standard resistors of value 10 ohms and higher. This design is also known as NBS Type.

A resistance element wound on an insulated metal tube is suspended in an oil filled outer can. A concentric inner tube supports the insulated resistor form and provides a thermometer well for insertion of a thermometer to determine the resistor ambient temperature.

The oil in the can provides heat transfer from the resistance element to the outer wall of the can. The whole container is also immersed in a temperature controlled oil bath for further stabilization of the temperature.

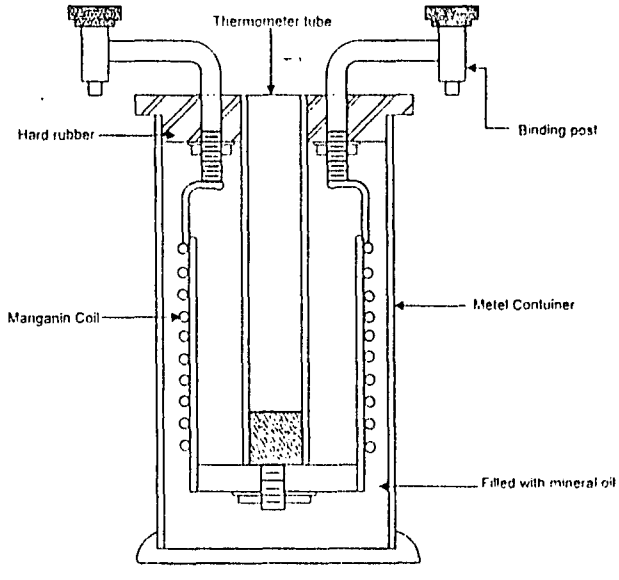


Figure 8.12-NBS one ohm type standard (Source : National Institute of Standards & Technology, U.S.A)

e) ESI SR IO4

ESI SR 104 is a 10 kiloohm transportable resistance standard manufactured by Electro Scientific Industries(Presently Tegam Inc.). The ESI SR 104 is widely used in standards

laboratories. It is also used in inter laboratory comparisons of resistance due its portability. The standard has its own oil bath.

The long term stability of the standard is specified as ± 1 ppm in the first year and ± 0.5 ppm/year after 2 years. The temperature coefficient is ± 0.1 ppm/°C at 23 °C. A built in temperature sensor that can be used to measure the internal temperature of the resistor is provided. A table of correction factors, to correct the resistance value to the local ambient temperature is also provided.

8.3.7 Capacitance standards

A number of different types of secondary standard capacitors are available. Those in the range 1 pF to 1000 pF are constructed with a solid dielectric or with an inert gas dielectric. Capacitors of 10 pF or 100 pF with solid dielectric (fused silica) are available. Gas dielectric capacitors of 5 pF and 10 pF are also used. Gas dielectric capacitors of higher value, 100 pF to 1 000 PF are made of piles of separated parallel plates in a hermetically sealed container with nitrogen as the dielectric.

Standard capacitors usually have either three terminals or five terminals. In the three terminal type a Faraday shield is used. The shield is connected to the third terminal. A schematic of the three terminal type capacitor is shown in Figure 8.13.

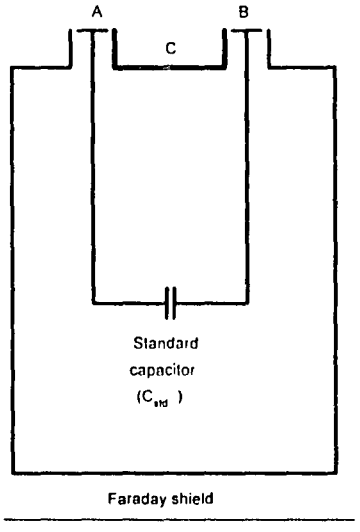


Figure 8.13-Three terminal type capacitor (Source : Fluke Corp.,U.S.A)

The two additional terminals of a five terminal capacitor enables a four terminal connection to be made, that is, one pair of terminals is used for current application and the other pair for measurement of voltage. The shield is used as in the case of a three terminal capacitor.

In parallel plate capacitors, a guard ring is used to reduce fringing, which occurs at the outer edges of the active plates. Generally secondary standard capacitors should be calibrated against a primary capacitance standard every two years or so.

8.3.8 Inductance standards

Although it is possible to construct calculable inductance standards by winding a conductor on an insulated core, this is generally not done as it is more prudent to construct accurate standard capacitors and assign values of inductance to them.

8.4 Working standards

8.4.1 Multifunction calibrator

The workhorse of the present day electrical calibration laboratory is the multifunction calibrator. The multifunction calibrator is a working standard used mainly for calibration of multimeters, though some models can be used as a dc voltage standard for ac-dc transfer

measurement of alternating voltages or as a low noise supply source for bridges and dividers.

The main features of currently available instruments are given here.

a) Calibrator functions and ranges

A typical multi function calibrator provides direct and alternating voltage and current as well as resistance and capacitance stimuli. Some instruments marketed as multi product calibrators also provide thermocouple and resistance thermometer stimuli.

The functions and output ranges of a typical multifunction calibrator are given in Table 8.1.

b) Output Drift

Most components of electrical instruments are subject to change due to effects arising from loading and ambient conditions (temperature, humidity etc.). This phenomenon is known as electrical drift. Due to this reason, the specifications of a calibrator are usually given for a time period. 90 days or one year specifications are common. This means that the stimuli of the calibrator are expected to be within the tolerance indicated during the time period given. At the

end of the time period a comparison against a higher level standard is required to determine the relative drift of the stimulus. Good quality calibrators should have small drift rates over a considerable period of time. Typical specifications of a modern multifunction calibrator are given Table 8.1

Table 8.1 Typical specifications of a multifunction calibrator

Function	Range	Best one year specification ppm or % of setting
DC Voltage	0 to ±1020V	±50 ppm
DC Current	0 to ±11A	±0.01%
Resistance	0 to 3.29.999 MΩ	±0.009%
AC Voltage,10 Hz to 500 kHz, Sine	1 mV to 1020V	±0.03%
AC Current,10 Hz to 10 kHz, Sine	29 µA to 11A	±0.06%
Capacitance	0.33 nF to 1.1 mF	±0.25%
Thermocouple	-250°C to +2316°C	±0.14°C
RTD Source	-200 to +630°C	±0.03°C
DC Power	109 µW to 11 kW	±0.08%
AC Power,45-65 Hz, PF=1	109 µW to 11 kW	±0.15%
Phase,10 Hz to 10 kHz	0 to ± 179.99°	±0.15°
Frequency	0.01 Hz to 2.0 MHz	±25 ppm

c) Burden Current

A calibrator operated the voltage mode has to supply a burden or load current. Since the input impedance of modern digital multimeter digital multimeter (DMM) is typically 10 MΩ or higher in the dc voltage ranges the burden current would be limited to about 0.1 mA at 1000 V. In the AC voltage range and for certain other applications burden currents of 20 mA or more may be required.

d) Compliance voltage

The voltage required to drive a constant current through the unit under test is known as the compliance voltage. In the case of digital multimeter (DMM) calibrations this voltage is the sum of the voltages across the digital multimeter (DMM) shunt (See Figure 8.16), lead resistances and contact resistances of the binding posts.

e) Protection

Protective circuits are incorporated in all well designed calibrators for guarding against erroneous connections. The calibrator should be able to tolerate a potentially dangerous short circuit or any other incorrect connection by switching to stand by mode.

f) Output noise

The output noise is a factor that must be taken into consideration in the selection of a calibrator. On a given range the output noise of the calibrator must be low enough to keep the least significant digit of the unit under test from being affected.

8.4.2 Process calibrator

A process calibrator is a portable instrument intended mainly for use in the field for trouble shooting and calibration of process control instrumentation. These rugged, battery operated calibrators are available as single function or multi function instruments. The typical functions and specifications of a process calibrator are given in Table 8.2.

Table 8.2 Functions and specifications of a typical process calibrator

Function	Resolution	Accuracy (1 Year)	
		Source	Measure
DC Voltage			
0 to 100 mV	0.01 mV	0.02% Rdg + 2 LSD	0.02% Rdg + 2 LSD
0 to 10V	0.001V	0.02% Rdg + 2 LSD	0.02% Rdg + 2 LSD
0 to 30V	0.001V	0.02% Rdg + 2 LSD	0.02% Rdg + 2 LSD
DC Current			
0 to 24 mA	0.001 mA	0.10□ to 1.0□	0.10□ to 1.0□
Resistance			
0Ω to 3200Ω	0.01Ω to 0.1Ω	0.05% Rdg	
15Ωto 3200Ω	0.01Ω to 0.1Ω	0.25% Rdg	
Frequency			
1 to 1000 Hz	1 Hz		
1.0 to 10.0 kHz	0.1 kHz		
Thermocouples			
Types J, K, T, E, N	0.1 to 1 °C	0.7 °C – 1.2 °C	0.7 °C – 1.2 °C
Types R, S, B,	1 °C	1.4 °C - 2.5 °C	1.4 °C - 2.5 °C
Resistance temperature detectors (RTD)			
Pt 100		0.3 °C	0.3 °C
Ni 120		0.2 °C	0.2 °C

LSD-Least significant digit

Rdg-Reading

8.4.3 Resistors

Present day working standard resistors usually do not require oil or air baths and therefore can be used for on site calibrations as well. Wire wound working standard resistors in the range of 10 ohm to 20 MΩ are available. Most resistors have temperature stability of typically less than 2 ppm over a temperature interval of ten degrees (18°C to 28°C). In most cases manufacturers supply calibration tables, listing corrections in 0.5°C increments. In good quality resistance standards permanent shift in resistance is typically less than 2 ppm after cycling between 0°C and 40°C.

9 Uncertainty of measurements

9.1 Introduction

The uncertainty to be assigned to a measurement result has been a widely debated subject from the very beginning of modern measurements. At least two different approaches for determining the total uncertainty had been used in the past namely the combining of uncertainties arithmetically or in quadrature (root sum of squared quantities). In 1990 the CIPM convened a group of experts to formulate a consistent set of rules to compute uncertainties of measurements. The group came out with a set of recommendations known as CIPM recommendations for computation of uncertainties. In 1993, International Organization for Standardization published the recommendations in the form of a guide. The guide is now widely used and is known as the ISO Guide for Measurement Uncertainties.

Since the publication of the recommendations of the International Committee of Weights Measures (CIPM) a consensus in the procedures for determining the combined uncertainty has emerged among a majority of the national standards laboratories. This is a positive development for everybody involved in metrology at all levels.

9.2 Basic Concepts

The basic objective of performing a measurement is to determine the value of a specific quantity, i.e. the value of a measurand. A measurement therefore begins with an appropriate specification of the measurand, the method of measurement and the measurement procedure.

Unfortunately the value of the measurand can not be determined exactly due to errors that arise during the measurement process. It is only possible to obtain an estimate for the value of the measurand. This estimate is complete only when it is supplemented by a statement indicating its inexactness, namely the uncertainty.

The terms *error*, *random error* and *systematic error* were used (See Chapter 1, Fundamental concepts) in the past to describe uncertainties and have caused much confusion. If we accept the fact that no measurement can be exact, then these terms can be defined unambiguously. In Chapter 1, *error* was defined as the difference between the result of a measurement and the *true value* of the measurand. Since the *true value* cannot be determined, the so-called *error* cannot be determined as well.

The concept of uncertainty relieves us of this problem. The word *uncertainty* means doubt and thus in its broadest sense *uncertainty of measurement* conveys the idea that the measurement result is not exact. The formal definition of the term as given in the current edition of the international vocabulary of metrology (VIM) is:

> *the parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand.*

This definition may be contrasted with two older concepts,

- a measure of the possible *error* in the estimated value of the measurand as provided by the result of a measurement.

- an estimate characterizing the range of values within which the *true value* of a measurand lies

(VIM , First edition, 1984, 3.09)

These two definitions are based on quantities that cannot be determined; the *error* of a result of measurement and the *true value* of a measurand respectively. These definitions are therefore ideals whose practical application is impossible. In the context of the present definitions it is best that the words *error* and *true value* are avoided in test reports and other technical documents.

9.3 Recommendations of the ISO guide

The main recommendations of the guide are summarized here. For fuller details and comprehnsive discussion of uncertainty concepts the guide must be consulted.

9.3.1 Types of Evaluation

Two methods of evaluation of measurement uncertainties, namely Type A and Type B are recommended in the guide.

a) Type A evaluation

In a Type A evaluation a series of repeated observations is obtained to determine the variance of the measurement result. The positive square root of the variance is referred to as a Type A standard uncertainty, (U_A).

b) Type B evaluation

In a Type B evaluation information found in calibration reports, certificates, manufacturer's specifications etc., are used to estimate a standard deviation known as a Type B standard uncertainty, (U_B).

The designations Type A and Type B are not new words for *random error* and *systematic error*. These are methods of evaluating uncertainty and could equally be applied to both random and systematic effects. e.g. The uncertainty of a correction for a known systematic effect may be obtained by either a Type A or Type B evaluation, as may be the uncertainty due to random effects of a measurement result .

c) Evaluation of Type A uncertainty

The mean value $\bar{q}$ of m independent observations $q_1, q_2, \ldots q_k, \ldots q_m$ is obtained from

$$\bar{q} = \frac{1}{m}\left(\sum_{k=1}^{m} q_k\right) \tag{9.1}$$

The variance of observations is given by

$$s^2 = \frac{1}{m-1}\sum_{k=1}^{m}(q_k - \bar{q})^2 \tag{9.2)}$$

The variance of the mean $\bar{q}$ is given by

$$s^2(\bar{q}) = \frac{s^2(q)}{m} \tag{9.3}$$

The number of observations m should be sufficiently large so that $\bar{q}$ provides a reliable estimate of the mean value and $s^2(\bar{q})$ provides a reliable estimate of the variance of the observations.

The Type A standard uncertainty $u_A(q)$ is obtained as,

$$u_A(q) = s(\bar{q}) = \frac{s(q)}{\sqrt{m}} \tag{9.4}$$

The number of degrees of freedom ν is given by :

$$\nu = m - c \tag{9.5}$$

Where m is the number of observations and c the number of constraints.

d) Evaluation of Type B uncertainty

In a Type B evaluation, the estimated variance $s^2(q)$ or standard deviation s(q) of a quantity q, is obtained by judgment using all relevant information on the possible variability of q. The pool of information may include previous measurement data, experience with or general knowledge of the behavior and properties of relevant materials and instruments, manufacturer's specifications, data provided in calibration and other certificates, and uncertainties assigned to reference data taken from handbooks.

The proper use of the pool of available information for a Type B evaluation of standard uncertainty calls for insight based on experience and general knowledge, but is a skill that can be learned with practice. It should be recognized that a Type B evaluation of standard uncertainty can be as reliable as a Type A evaluation, especially in a measurement situation where a Type A evaluation is based on a comparatively small number of statistically independent observations.

The following guidelines are used for obtaining Type B evaluations :

a) A stated confidence interval having a stated level of confidence such as 95 or 99 percent should be converted to a standard uncertainty by treating the quoted uncertainty as if a normal distribution had been used to calculate it and dividing it by the appropriate factor for such a distribution. These factors are 1.960 and 2.576 for the two levels of confidence given.

b) If a confidence interval with the stated level of confidence and degrees of freedom are given, (e.g 95 or 99 percent confidence level with 12 degrees of freedom), then to obtain the standard uncertainty, divide the semi-confidence interval by the student's t-value corresponding to the degrees of freedom.

c) If an expanded uncertainty and k factor are given, divide the expanded uncertainty by the k factor to obtain the standard uncertainty.

d) Model the quantity by a uniform, rectangular or triangular probability distribution and estimate the lower and upper limits a- and a+ for the value of the quantity in question such that, the probability that the value lies in the interval a- to a+ for all practical purposes is 100 percent. The best estimate of the mean value of the quantity is then (a- + a+) /2.

For a rectangular distribution the standard uncertainty is given by,

$$u_B = \frac{a}{\sqrt{3}} \tag{9.6}$$

where $a = (a_+ - a_-)/2$, i.e. the semi interval.

If the distribution used to model the quantity is triangular rather than rectangular, then

$$u_B = \frac{a}{\sqrt{6}} \tag{9.7}$$

The degrees of freedom to be associated with the standard uncertainty obtained from a Type B evaluation is obtained frcm the following equation :

$$\nu_i = \frac{1}{2}\left[\frac{\Delta u(\bar{q})}{u(\bar{q})}\right]^{-2} \tag{9.8}$$

where,

$u(\bar{q})$ - standard uncertainty of $\bar{q}$

$\Delta u(\bar{q})$ - uncertainty of standard uncertainty

$\frac{\Delta u(\bar{q})}{u(\bar{q})}$ - relative uncertainty of standard uncertainty

9.3.2 Determination of combined standard uncertainty and effective degrees of freedom

In many instances a measurement result is obtained by the use of an equation which combines different input quantities. The equation represents the relationship between the measurand and physical quantities on which the measurand is dependant. In such cases the uncertainty of the measurand is computed by combining the standard uncertainties of the input quantities as a combined standard uncertainty.

a) Combined Standard Uncertainty

The combined standard uncertainty of a measurement result y related to input values x_1, $x_2, \ldots x_n$ by the relationship,

$$y = f(x_1, x_2, \ldots\ldots, x_n) \tag{9.9}$$

is given by,

$$U_c^2(y) = \left(\frac{\partial f}{\partial x_1}\right)^2 U^2(x_1) + \left(\frac{\partial f}{\partial x_2}\right)^2 U^2(x_2) + \ldots\ldots + \left(\frac{\partial f}{\partial xn}\right)^2 U^2(x_n) \tag{9.10}$$

where $U(x_i)$ is a standard uncertainty evaluated as described in the previous section (Type A evaluation or Type B evaluation) for each input quantity. Equation (9.10) is valid only when the input quantities x_1, x_2, x_3, ... x_n are independent i. e. uncorrelated. If the input quantities are correlated then the co-variances have to be taken into account . The following equation applies:

$$U_c^2(y) = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2 U^2(x_i) + 2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \left(\frac{\partial f}{\partial x_i}\right)\left(\frac{\partial f}{\partial x_j}\right) U(x_i, x_j) \tag{9.11}$$

In this equation the terms $U(x_i, x_j)$ are the covariances of the input parameters x_i and x_j where j=i+1. Equation (9.11) is known as the *Law of Propagation of Uncertainties.* When the input quantities are independent (not correlated) the second term in equation (9.11) is zero and equation (9.10) results.

b) Effective degrees of freedom

Welch-Satterthwaite formula

The effective degrees of freedom of the combined standard uncertainty are obtained from the Welch-Satterthwaite formula given below:

$$\nu_{eff} = \frac{u_c^4(y)}{\sum_{i=1}^{n} \frac{u_i^4(y)}{\nu_i}} \tag{9.12}$$

where,

$$U_i(y) = \left(\frac{\partial f}{\partial x_i}\right) U(x_i)$$

v_i - degrees of freedom of input uncertainty U_i (y)

The value of v'_{eff} resulting from equation (9.12) may not be an integer. In this case v'_{eff} is obtained by rounding down to the next lower integer.

9.3.3 Expanded uncertainty

The expanded uncertainty is analogous to the confidence interval of a measurement result. The expanded uncertainty **U** is obtained by multiplying the combined standard uncertainty $u_C(y)$ by a coverage factor **k**

$$U = k \, . \, U_C(y) \qquad (9.13)$$

The result of a measurement is then expressed as y ± **U** at a confidence level of 95 percent or 99 percent. The value of the coverage factor **k** is chosen on the basis of the desired level of confidence to be associated with the interval y - **U** to y + **U**. In general **k** is chosen in the range 2 to 3.

The method of choosing **k** using the effective degrees of freedom v_{eff} and student's t - distribution is explained in the examples.

9.4 Examples of uncertainty calculations

9.4.1 Example 1 - Determination of the uncertainty of the value of a test mass

a) Experimental data

The value of a stainless steel mass of nominal value one kilogram is determined by carrying out double substitution weighing in a single pan balance, using a reference standard mass of known value and uncertainty. The weighing operation is repeated ten times and the results are given in Table 9.1.

Table 9.1-Weighing results for calibration of a test mass

No	Value of test mass g
1	1000.143
2	1000.144
3	1000.144
4	1000.146
5	1000.146
6	1000.146
7	1000.144
8	1000.143
9	1000.145
10	1000.145

Mean value of test mass = 1000.1446 g

Standard deviation = 0.0011 g

Standard deviation of the mean = 0.0011/ $\sqrt{}$ 10 = 0.00035 g

b) Estimation of Combined Standard Uncertainty $U_c(y)$

The contributory uncertainties arise from,

a) Variability of the weighing procedure quantified by the standard deviation of the mean given above.

b) The uncertainty of the mass standard used. This is taken from the calibration certificate of the standard mass and is given as 0.005 g at 95% confidence level with 14 degrees of freedom.

c) The uncertainty arising from the resolution of the digital display of the balance used for the comparison, 0.001 g. Usually this is treated as having a rectangular probability distribution and the standard uncertainty is computed by dividing the half interval by $\sqrt{3}$ .However, since in a double substitution weighing, a difference of two weighings is computed, this figure is multiplied by $\sqrt{2}$., i. e .0005x$\sqrt{2}$./ $\sqrt{3}$ g.

The uncertainty budget

Source of Uncertainty	Type of evaluation	Standard uncertainty	Degrees of freedom
Variability of observations	A	0.00035 g	9
Reference mass standard	B	0.0025 g	14
Resolution of the digital display	B	0.00020 g	infinity

Estimation of the combined standard uncertainty of the mean value is given below:

Combined standard Uncertainty, $U_C(y)$ = $(0.00035^2+0.0025^2+0.00020^2)^{1/2}$

= 0.00253 g

= 0. 002 g (rounded off to one significant figure)

c) Effective degrees of freedom

The effective degrees of freedom is computed using equation (9.12):

$$\nu_{eff} = \frac{0.002^4}{\frac{0.00035^4}{9} + \frac{0.0025^4}{14} + \frac{0.00020^4}{\infty}} = 9.6$$

This is rounded down to 9 degrees of freedom.

d) Expanded Uncertainty

To determine expanded uncertainty, it is necessary to choose a coverage factor, **k.** The coverage factor is taken from the t - tables, corresponding to 9 degrees of freedom and 95% confidence level,

$t_{95,9}$ = 2.26

Expanded Uncertainty, **U** = 2.26 x 0.002

= 0.0045 g

e) Reporting of the result

The result is reported as,

Value of the test mass = 1000.145 g

Expanded uncertainty = ± 0.005 g with k = 2.26 at 95% confidence level and 9 degrees of freedom.

or

The value of the test mass is 1000.145 g ± 0.005 g with k = 2.26 at 95% confidence level and 9 degrees of freedom.

9.4.2 Example 2-Determination of the value of a test resistance

A test resistance is calibrated using a direct reading digital multimeter and resistance standard. The test resistance is measured 10 times using the digital multimeter and the reading ρ_x is noted down. The standard resistance is then measured 10 times using the same multimeter and the corresponding reading ρ_s is noted down.

The value of the test resistance (R_x) is calculated using the equation :

$$R_x = R_s \frac{\bar{\rho}_x}{\bar{\rho}_s} \qquad (9.14)$$

Where R_s is the calibrated value of the standard resistance, $\bar{\rho}_x$ the mean of ρ_x and $\bar{\rho}_s$ the mean of ρ_s

a) Experimental data

The experimental data are given below :

$\bar{\rho}_x$ = 100.051 Ω

Standard deviation = 18 ppm

$\bar{\rho}_s$ = 100. 001 Ω

Standard deviation = 19 ppm

R_s = 99.999 Ω

Expanded uncertainty = 20 ppm at k=2 with 9 degrees of freedom.

To calculate the value of the test resistance and its uncertainty, we proceed as follows

b) Value of test resistance

Using equation (9.14),

$$R_x = 99.999_s \frac{100.051}{100.001} = 100.0489 \ \Omega$$

c) Calculation of Uncertainty

The main uncertainty components are :

a) Transfer uncertainty of the digital multimeter.

b) Calibration uncertainty of the standard resistor.

Transfer Uncertainty of the Digital Multimeter (Type A)

Since both test and standard resistances are measured using the same digital multimeter under similar conditions it is possible to determine the transfer uncertainty as a pooled standard deviation of the two measurement standard deviations.

Pooled $s = \sqrt{\frac{18^2 + 19^2}{2}} = 18.5$ ppm with 18 degrees of freedom (18 = 10x2 –2)

Standard deviation of the mean $= U_{tr} = \frac{18.5}{\sqrt{10}} = 5.8$ ppm

Standard uncertainty = U_{tr} = 5.8 ppm with 18 degrees of freedom.

Calibration uncertainty of the standard resistance (Type B)

This is given as 20 ppm at k=2,

Standard uncertainty, $U_{Rx} = \frac{20}{2} = 10$ ppm

d) Combined Standard Uncertainty

The combined standard uncertainty is computed as :

$$U_{Rx} = \sqrt{5.8^2 + 10^2} = 11.56 \text{ ppm}$$

e) Effective Degrees of Freedom

The effective degrees of freedom is computed using equation (9.12) as :

$$v_{eff} = \frac{11.56^4}{\frac{5.8^4}{18} + \frac{10^4}{9}} = 15.21 \quad \text{round down to 15}$$

The t-value for 95 % confidence level and 15 degrees of freedom is 2.13.

k = 2.13

f) Expanded Uncertainty

U = 2.13 x 11.56 = 24.56 ppm round off to 25 ppm.

g) Reporting of Results

The value of the test resistor = 100.049 Ω ± 0.002 Ω at 95 % confidence level with 15 degrees of freedom.

9.4.3 Example 3 - Calibration of a digital thermometer

A digital thermometer having a resolution of 0.01°C and a sensor of Type K thermocouple is calibrated in comparison with a working standard platinum resistance thermometer. The comparison is carried out in a stirred oil bath in the temperature range 0°C to 300°C. The details of the standards used and the experiment are given below:

a) Standards and auxiliary equipment:

Working standard PRT:

Calibration Range	-	0 to 630°C
Triple point resistance	-	24.9985 Ω
$a = -2.0307883 \times 10^{-4}$		$b = -2.8967225 \times 10^{-5}$
Uncertainty		±0.0025°C at 95% confidence level with 8 degrees of freedom.

Oil Bath:

Uniformity	-	±0.006°C,
Stability	-	±0.006°C,

Resistance Bridge:

Type	- DCC Bridge
Accuracy	- 0.2 ppm of reading + 1 step of digit

Resistance Standard (R_S)

Value at 25°C	- 9.9998 Ω
Uncertainty	- ±2 ppm = 9.9998 x 2 x 10^{-6} = ±2 x $10^{-5}\Omega$ at 95 % with 9 degrees of freedom

b) Summary of Experimental results.

The summary of the experimental results is given in Table 9.2

c) Estimation of combined standard uncertainty of PRT temperature.

The uncertainty of the temperatue measured by the PRT consists of a number of components arising from different sources. An analysis of the prime sources is indicated in the Ishikawa diagram of Figure 9.1.

Each of these components are evaluated below:

PRT:

The uncertainty of the PRT is mainly due to its calibration uncertainty, which is quoted as ±0.0025°C at 95% confidence level, with 8 degrees of freedom.

$$U_{PRT} = \frac{0.0025}{2.31} = 0.0011$$

2.31 - t value for 8 degrees of freedom at 95% confidence level.

TABLE 9.2 - Experimental results of comparison of a standard prt and digital thermometer

Test point	WPRT			Digital thermometer		
	Reading	Mean	Std. dev.	Reading	Mean	Std. dev.
0(Ice Point)	-0.003			-0.08		
	-0.002			-0.08		
	-0.003	-0.003	0.001	-0.08	-0.08	0
25	25.172			25.09		
	25.161			25.10		
	25.161	25.165	0.006	25.13	25.107	0.021
50	51.212			51.34		
	51.221			51.37		
	51.261	51.231	0.026	51.37	51.36	0.017
100	103.541			103.45		
	103.497			103.43		
	103.518	103.519	0.022	103.43	103.437	0.012
150	155.581			155.36		
	155.587			155.38		
	155.569	155.579	0.009	155.36	155.367	0.012
200	207.461			207.37		
	207.495			207.37		
	207.528	207.495	0 033	207.42	207.39	0.026
300	309.717			311.39		
	309.726			311.37		
	309.734	309.726	0.009	311.28	311.347	0.059
Pooled std. deviation =0.0188				Pooled std. deviation =0.0271		

Resistance Measurement:

The uncertainty of the measurement of resistance using a bridge arises from two components, namely the uncertainty of the bridge itself and the uncertainty of the standard resistor used for the comparison.

The uncertainty of the standard resistor itself consists of two components, namely

i) Calibration uncertainty of the standard resistor

ii) Uncertainty arising from the temperature variation of the resistor

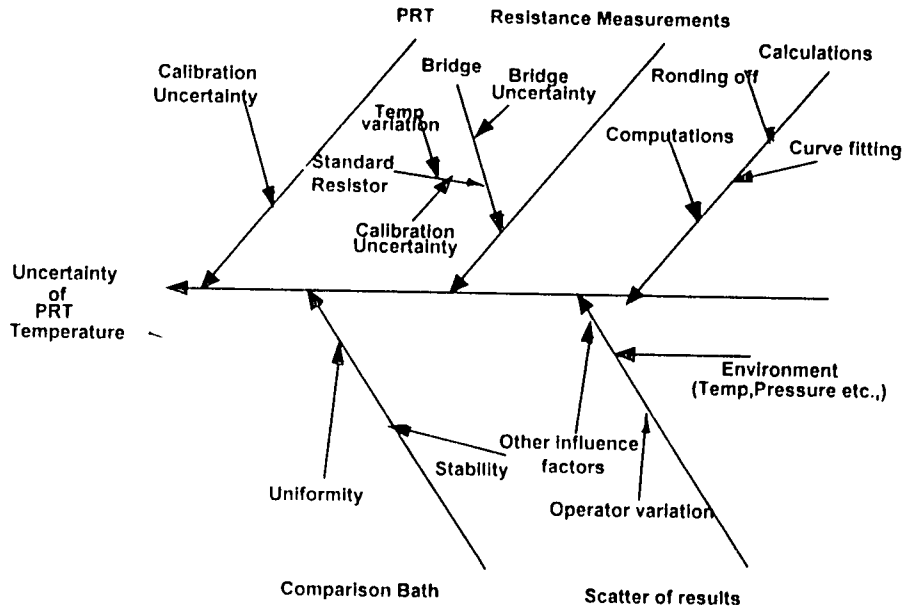


Figure 9.1-Ishikawa diagram for uncertainty components of PRT temperature

Effects (i) and (ii) are quantified as shown below:

Effect (i)

Calibration uncertainty of resistor $= 2 \times 10^{-6} \times 9.9998\ \Omega$

$= 19.9998 \times 10^{-6}\ \Omega$

$$U_{SRC} = \frac{19.9998 \times 10^{-6}}{2.26(\text{t-value})} = 8.8494 \times 10^{-6}\ \Omega$$

$\nu_{SRC} = 9$

Effect (ii)

If the standard resistor is subject to a maximum variation of ±1°C (temperature variation in a typical laboratory)

$dt = 1°C$

$R_t = R_0 [1 + \alpha (t - t_0) + \beta (t - t_0)^2]$

$dR_t = R_0 (\alpha\ dt + \beta . 2. (t - t_0)\ dt)$

Since $R_0 = 9.9998\ \Omega$

$\alpha = 9.9 \times 10^{-6}\ \Omega/°C$

$\beta = -5.8 \times 10^{-7}\ \Omega/(°C)^2$

$t = 23$ & $dt = 1$

$dR_t = 9.9998\ [9.9 \times 10^{-6} + (-5.8 \times 10^{-7}) . 2 \times (23-25) \times$

$dR_t = 122.20 \times 10^{-6}\ \Omega$

Since the temperature variation in the laboratory could be taken to be approximately sinusoidal in time, the standard uncertainty is obtained as,

$$U_{SRt} = \frac{122 . 20 \times 10^{-6}}{\sqrt{2}} = 86 . 41 \times 10^{-6}\ \Omega$$

Assuming the reliability of the laboratory temperature variation to be about 75 percent, the degrees of freedom are given by,

$$\nu = 1/2 \times 0.25^{-2} = 8$$

The combined uncertainty due to the two effects is given by,

$$U_{SR}^2 = (8.8494 \times 10^{-6})^2 + (86.41 \times 10^{-6})^2$$

$$U_{SR} = 86.87 \times 10^{-6}\ \Omega$$

The effective degrees of freedom of the uncertainty of the standard resistor is,

$$\nu_{eff,Rs} = \frac{(86.87 \times 10^{-6})^4}{\frac{(86.41 \times 10^{-6})^4}{8} + \frac{(8.8494 \times 10^{-6})^4}{9}}$$

$$= 8.17$$

Round down to 8 degrees of freedom.

Uncertainty of resistance measurement:

In order to estimate the combined uncertainty of the resistance measurement, we have to consider the combined effect of the uncertainty of the standard resistor and the bridge uncertainty.

The measured resistance of the PRT, R_X is related to the value of the standard resistor R_S and the bridge reading ρ, by the following equation,

$$R_X = R_S \cdot \rho$$

Since R_S and ρ are quite independent, we can write the uncertainty propagation equation,

$$U^2_{R_X} = \left(\frac{\partial R_x}{\partial R_s} U_s\right)^2 + \left(\frac{\partial R_x}{\partial \rho} U_\rho\right)^2$$

Now $\frac{\partial R_x}{\partial R_s} = \rho$ and $\frac{\partial R_x}{\partial \rho} = R_s$. Also at balance the bridge reading is 5.5654 and

$$U_\rho = \frac{(0.2 \times 5.5654 \times 10^{-6} + 0.000\ 000\ 01)}{\sqrt{3}} = 0.6416 \times 10^{-6}$$

Substituting in the above equation

$$U_x^2 = (5.5654 \times 86.87 \times 10^{-6})^2 + (9.9998 \times 0.6416 \times 10^{-6})^2$$

$$= (483.47)^2 \times 10^{-12} + (6.42)^2 \times 10^{-12}$$

$$U_X = 483.51 \times 10^{-6}\ \Omega$$

Conversion to °C

In order to compute the final combined standard uncertainty in temperature units (°C), the above uncertainty has to be converted. For this purpose we use the transfer equation of the WPRT, namely,

$R_t = R_o(1 + a(t-t_o) + b(t-t_o)^2$

differentiating with respect to t we obtain,

$dR_t = Ro[a + 2.b.(t-t_o)]\ dt$

Substituting the values for a,b, R_o and t_o we obtain,

$dt=-26.06dR_t$

For $dR_t=483.51\times10^{-6}\ \Omega$

$dt=26.06 \times 483.51 \times 10^{-6} = \underline{0.013}\ °C$

The effective degrees of freedom of the uncertainty of the resistance measurement is obtained from,

$$v_{eff,R} = \frac{(483.51\times10^{-6})^4}{\frac{(483.47\times10^{-6})^4}{8} + \frac{(6.42\times10^{-6})^4}{8}}$$

$= 8$

Uncertainty due to Bath temperature variations:

The uncertainty arising from the temperature variations of the bath consists of,

Bath Stability = ±0.006°C

Bath Uniformity = ±0.006°C

Since both of the above figures are given as upper and lower bounds, we may assume a rectangular distribution for each of them.Thus,

$$u_{bs} = \frac{0.006}{\sqrt{3}} = 0.003$$

$$u_{bu} = \frac{0.006}{\sqrt{3}} = 0.003$$

$$U_b = \sqrt{2}\,x\,0.003 = 0.004\,°C$$

The degrees of freedom are evaluated from equation (9.8). The uncertainty on account of stability and uniformity of a bath may be relied upon to about 50%. (depending on the age of the bath)

$$v = 1/2[0.5]^{-2} = 2 \quad \text{for each component}$$

$$v_{eff,b} = \frac{(0.004)^4}{2\times\frac{(0.003)^4}{2}}$$

$= 3.16$

round down to 3

Scatter of results:

From the information given in Table 9.2, a pooled standard deviation is calculated,

$$S_{pd} = \sqrt{\frac{S_1^2 + S_2^2 + \ldots + S_7^2}{7}}$$

$= 0.0188°C$

The standard deviation of the mean is,

$$SDOM = \frac{0.0188}{\sqrt{3}}$$

$$= \quad 0.0109°C$$

$$U_R \quad = \quad 0.0109\ °C$$

with 20 degrees of freedom (3 x 7 - 1).

Table 9.3- Summary of Uncertainty Components

Source of uncertainty	Type of evaluation	Standard uncertainty,°C	No. of degrees of freedom
Platinum resistance thermometer Calibration	B	0.001	8
Resistance measurement Combined standard uncertainty	B	0.013	8
Calibration bath Uniformity and stability combined	B	0.004	3
Scatter Pooled std. deviation	A	0.0109	20

Combined standard deviation $= \sqrt{(0.001^2 + 0.013^2 + 0.004^2 + 0.0109^2)} = 0.017\ °C$

The effective degrees of freedom is obtained from,

$$v_{eff,T} = \frac{(0.017)^4}{\frac{(0.001)^4}{8} + \frac{(0.013)^4}{8} + \frac{(0.004)^4}{3} + \frac{(0.0109)^4}{20}} = 21.3$$

round down to the nearest integer to give $v_{eff,T}$ = 21 degrees of freedom.

d) Expanded Uncertainty:

From t - tables, t = 2.045 for 21 degrees of freedom at 95% confidence level.

$$k \quad = \quad 2.045$$

and $$U \quad = \quad 2.045 \times 0.017$$

$$= \quad 0.03$$

Rounding off to one significant figure, **U** = ±0.03°C

e) Reporting of results:

The above uncertainty is calculated for the maximum experimental temperature of 300°C. This figure may be treated as the limit of uncertainty for the lover temperatures as well, since the major component of the uncertainty is from the scatter of results and is similar for the lower temperatures as well, (except the ice point).

The uncertainty result may be reported as, "The expanded uncertainty of the temperature measured by the working standard platinum resistance thermometer evaluated as a combination of Type A and Type B uncertainties is ±0.03°C with k = 2.045 at 95% confidence level with 21 degrees of freedom".

9.4.4 Example 4- Calibration of 1 Kilogram Weight with buoyancy corrections

a) Experimental details

The mass of a one kilogram weight is determined by comparing it against a reference standard mass using a mass comparator. The experiment is repeated 10 times and the mass value of the test weight, after applying buoyancy corrections is determined.

The values of the reference standard mass and the experimental results are given below :

Reference standard :

Conventional mass value M_s = 1000.003281g

Expanded uncertainty : The expanded uncertainty at a coverage factor , k=2 at 95% level of confidence is given as ± 0.015 mg.

The buoyancy corrected mass values determined using equation (9.15) are given in Table 9.4.

$$M_X^{\Lambda} = M_S^{\Lambda} \frac{(1-\frac{\rho_a}{\rho_X})(1-\frac{\rho_a}{\rho_w})}{(1-\frac{\rho_a}{\rho_w})(1-\frac{\rho_a}{\rho_w})} \qquad (9.15)$$

Table 9.4 –Buoyancy corrected test mass values

Observation	Buoyancy corrected conventional mass value , g
1	999.998 817
2	999.998 836
3	999.998 830
4	999.998 859
5	999.998 911
6	999.998 920
7	999.998 933
8	999.998 865
9	999.998 872
10	999.998 916
Arithmetic Mean	999.998 876 g
Standard deviation	0.000042 g

b) Scatter of measurements (Type A evaluation)

On account of the dispersion in the ten values obtained during comparison against the reference standard mass, statistical method is used for Type A evaluation of standard uncertainty.

Standard uncertainty (U_{MA}) = 0.000042 / √ 10 = 0.000013 g

c) Uncertainty of the standard reference mass (Type B evaluation)

Standard uncertainty of the mass value of the reference standard is calculated using the expanded uncertainty as quoted in the calibration certificate and the quoted coverage factor k.

Standard uncertainty (U_{MS}) = .000 015 /2 = 0.000 0075 g

d) Uncertainty of buoyancy correction (Type B evaluation)

The uncertainty of the buoyancy corrected apparent mass value given by equation (9.15) is estimated by the application of the law of propagation of uncertainties as given below :

$$U_{MX}^2 = U_{MS}^2\left(\frac{\partial M_X}{\partial M_S}\right)^2 + U_{\rho_a}^2\left(\frac{\partial M_X}{\partial \rho_a}\right)^2 + U_{\rho_x}^2\left(\frac{\partial M_X}{\partial \rho_x}\right)^2 + U_{\rho_s}^2\left(\frac{\partial M_X}{\partial \rho_s}\right)^2 \quad (9.16)$$

By partial differentiation of equation () with respect to S, ρ_a, ρ_x and ρ_s the following derivatives are obtained :

$$\frac{\partial M_X}{\partial M_S} = \frac{\left(1-\frac{\rho_o}{\rho_x}\right)\left(1-\frac{\rho_a}{\rho_s}\right)}{\left(1-\frac{\rho_o}{\rho_s}\right)\left(1-\frac{\rho_a}{\rho_x}\right)} = D \quad (9.17)$$

$$\frac{\partial M_X}{\partial \rho_a} = \frac{M_S(\rho_s-\rho_x)}{(\rho_x-\rho_a)(\rho_s-\rho_a)} = E \quad (9.18)$$

$$\frac{\partial M_X}{\partial \rho_x} = \frac{M_S(\rho_s-\rho_a)(\rho_o-\rho_a)}{(\rho_s-\rho_o)(\rho_x-\rho_a)^2} = F \quad 9.19)$$

$$\frac{\partial M_X}{\partial \rho_x} = \frac{M_S(\rho_x-\rho_o)(\rho_a-\rho_o)}{(\rho_x-\rho_a)(\rho_s-\rho_o)^2} = G \quad (9.20)$$

ρ_o = 1.2 kg/m^3

ρ_a = 1.13 kg/m^3

ρ_s = 7912.72 kg/m^3

ρ_x = 8214.56 kg/m^3

U_{MS} = 7.5 x10^{-9} kg

U_{ρ_a} = 0.006 kg/m^3

U_{ρ_x} = 0 .640 kg/m^3

U_{ρ_s} = 0.650 kg/m^3

The sensitivity co-efficients D, E, F and G are calculated using equations (9.17), (9.18), (9.19) and (9.20) and the values of the above input quantities:

D = 1.000000325 E = -4.64504E-06 F=1.03766E-09 G= -1.11835E-09

The combined standard uncertainty U_{MX} is computed using equation (9.16) :

Combined standard uncertainty (U_{MX}) = 0.029 mg

e) Expanded uncertainty

The expanded uncertainty is obtained by multiplying the combined standard uncertainty by a coverage factor of 2.

Expanded uncertainty = 2 x 0.029 mg= 0.058 mg

9.4.5 Example 5- A Simple Case of Correlated Input Quantities

Ten resistors, each of nominal resistance of 1000 ohms, are connected in series (using cables of negligible resistance) in order to obtain a reference standard resistor of nominal value 10 kΩ .

Each one of the ten resistors R1. R2 --- R10 has been calibrated in comparison with another standard resistor R, of value 10 00 Ω ± 100 mΩ. Thus, through this calibration, all resistors R1, R2,RI0 become correlated and their measured value is 1 000 Ω ± 100 mΩ each.

In such a case :

$$R_{ref} = \sum_{1}^{10} R_i = R_1 + R_2 + ... + R_{10} = 10000\,\Omega$$

and U(Ri) = U(Rs) = 100 mΩ

assuming that no additional uncertainty is added during the calibration of individual resistors against the standard resistor R_s,

$$U_c(R_{ref}) = \sum_{i=1}^{10} U(R_i) = 10\,U(Rs) = 1\,\Omega$$

giving R_{ref} = 10 000 Ω ± 1 Ω

This type of uncertainty evaluation may also be used in other cases such as adding several standard masses or gauge blocks to obtain a standard of higher denomination

9.4.6 Example 6-Determination of the volume of a cylinder

The volume V of a cylinder with diameter D and height H is determined from micrometer measurements of V and H and the equation,

$V = \pi (D/2)^2 H$

Assume that the data, measured to the nearest half division (0.0005cm) on a properly zeroed micrometer are as follows.

D (cm)	H (cm)
1.0075	1.0105
1.0085	1.0115
1.0095	1.0115
1.0060	1.0110
1.0085	1.0100
1.0080	1.0115
Average $\overline{D}$ = 1.0080	$\overline{H}$ = 1.0110

Std. Dev s_D = 0.00118 s_H = 0.00063

Calculate the best estimate of the volume of the cylinder and its expanded uncertainty.

Solution

The best estimate of the volume, V is calculated as

$V=\pi (\overline{D}/2)^2 \overline{H}$ = 0.8068 cm^3

The major sources of the uncertainty in the measurement are ,

Variability in the measurement of $\overline{D}$.

Variability in the measurement of $\overline{H}$.

Uncertainty of the calibration of the micrometer.

Resolution of the micrometer

a) Type A evaluation of standard uncertainty

Effects 1 and 2 are amenable to Type A evaluation.

s_D = 0.00118 s_H=0.00063

SDOM= $s_D/\sqrt{6}$ SDOM=$s_H/\sqrt{6}$

$U(\overline{D})$=0.00048 cm $U(\overline{H})$=0.00026 cm

b) Type B evaluation of standard uncertainty

In order to do a Type B evaluation, one must be able to do two things; first, put some limit on the uncertainty for each component being evaluated; and then choose a probability distribution within each of those limits.

For the present case, the uncertainty in a micrometer calibration is generally accepted as a tolerance interval of ± 1 division. The micrometer has been built to this tolerance by the manufacturer and has hopefully been verified by a later calibration. In any case, assume that there is no knowledge of where inside the ±1 division (=□0.001cm) the reading lies. The standard uncertainty of the micrometer's tolerance can be estimated as ,

$$U(t) = 0.001 / \sqrt{3} = 0.00058 \text{ cm}$$

The factor $\sqrt{3}$ comes from assuming a rectangular probability distribution within the limits; namely the likelihood is the same for the micrometer calibration being anywhere within ± 1 division of the indicated reading.

The effect due to the resolution of the micrometer is analysed in the same way as is the micrometer's calibration tolerance: choose limits and then a probability distribution. Since data were taken by reading the micrometer to the nearest ½ division, the resolution limits are □ ¼ division. Further, the probability distribution should be rectangular within those limits, so

$$U(r) = 0.000025/ \sqrt{3} = 0.00014$$

c) Combined Standard Uncertainty

The combined standard uncertainty is obtained by applying equation (9.10). The sensitivity co-efficients $\frac{\partial F}{\partial x_i}$ appearing in that equation are obtained from the equation for V as follows :

$$C(D) = \frac{\partial \overline{V}}{\partial \overline{D}} = \pi(\overline{D}/2)\overline{H}$$

$$C(H) = \frac{\partial \overline{V}}{\partial \overline{H}} = \pi(\overline{D}/2)^2$$

$$C(t) = \frac{\partial \overline{V}}{\partial t} = \left(\frac{\partial \overline{V}}{\partial \overline{D}}\right)\left(\frac{\partial \overline{D}}{\partial t}\right) + \left(\frac{\partial \overline{V}}{\partial \overline{H}}\right)\left(\frac{\partial \overline{H}}{\partial t}\right)$$

$$\frac{\partial \overline{D}}{\partial t} \rightarrow \frac{\partial(\overline{D} + t)}{\partial t} = 1$$

$$C(t) = \pi\left(\overline{D}/2\right)\overline{H}.(1) + \pi(\overline{D})^2(1)$$

and C(p) = C(t)

Assuming that the measurements of D and H were taken separately, we can assume that the individual measurements of D and H are un-correlated. Then the combined standard uncertainty is given by summing over uncertainty components 1 through 4.

$$U_c^2 = C(D)^2 u(\overline{D})^2 + C(H)^2 u(\overline{H})^2 + C(t)^2 u(t)^2 + C(p)^2 u(p)^2$$

$$= (1.60)^2(0.00048)^2 + (0.80)^2(0.00026)^2 + (2.40)^2(0.00058)^2 + (2.40)^2(0.00014)^2$$

$U_c = 1.638 \times 10^{-3}$ cm^3

d) Effective Degrees of Freedom

Effects 1 & 2 degrees of freedom = 6-1 = 5

For effect 3 ,the degrees of freedom could be estimated from equation (9.8) as $(1/2)(0.5)^{-1/2} = 2$

In effect 4, the estimation is made with almost 100 % confidence. Therefore the number of degrees of freedom is infinity.

Application of Welch – Satterthwaite formula gives , v_{eff} = 3.7. Round down to 3 . For 95 % confidence level and for v =3 , t = 3.2 .

e) Expanded Uncertainty

$U = 3.2 \times 1.638 \times 10^{-3} = 0.00052$ cm^3

10 Calibration of dimensional standards and measuring instruments

10.1 General conditions

10.1.1 Reference conditions

The reference temperature for dimensional measurements is 20 °C. If a temperature different from 20 °C is used a correction using the linear co-efficient of expansion of the material is made. (See Table 3.2). All test items such as gauge blocks, end bars (rods), micrometers and vernier calipers should be kept in the temperature controlled room, for at least one hour prior to the commencement of calibration to attain temperature equalisation.

10.1.2 Reference standard

The hierarchy of length measurement standards is given in Figure 10.1. This diagram gives the next higher-level standard that may be used for the calibration of a given standard or instrument. The iodine stabilised Helium Neon laser is the primary standard. Secondary standards are those calibrated against the primary standard, namely the gauge block interferometer, helium neon laser interferometer and measuring machine, and helium neon laser interferometer coupled tape bench. Working standards are gauge blocks, line standards, standard tapes, ring gauges and dial gauge calibrators.

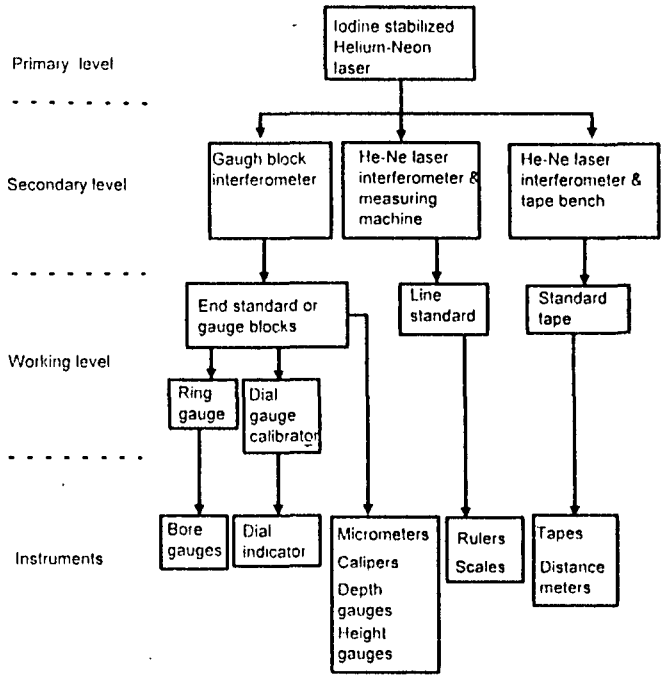


Figure 10.1 Hierarchy of length measurement standards

10.2 Calibration of standards

10.2.1 Gauge blocks

a) Reference Standard

The highest level gauge blocks, that is those of ISO 3650 Grade K and OIML Class AA are calibrated against a secondary standard i.e. He-Ne laser gauge block interferometer.

Working standard gauge blocks are calibrated by comparing them against a set of Grade K gauge blocks in a gauge block comparator, Figure 10.2.

b) Preparation

Clean the gauge blocks using a non-toxic solvent to remove preservative. Rubber gloves must be used in the cleaning process. Dry the gauge blocks using tissues and repeat the cleaning procedure until all visible preservative has been removed from the gauge block surfaces.

Visually inspect the gauging surfaces on all blocks for scratches, burrs, and particularly for imbedded grit, which will damage wringing surfaces. Those appearing to have surface defects may be compared to sample blocks known to conform approximately to the maximum limits.

The gauge block set is placed in the laboratory(temperature controlled atmosphere) and allowed to normalize for a period of not less than sixteen (16) hours before the calibration is initiated.

c) Flatness inspection

The flatness of each wringing surface is determined using an optical flat in both directions parallel to the edges across the middle of the block and from one edge to the other.

Prior to conducting the flatness test, clean each gage block using alcohol (C_2H_5OH). Clean optical flat using the same alcohol.

Place the optical flat on the gage block positioned under a source of monochromatic light and gently slide the flat until fringe patterns appear. Tip the optical flat slightly until contact is made at one edge. Fringe patterns will appear across the blocks parallel to the line of contact in the position for the first reading. While maintaining this general line of contact, adjust the angle of the optical flat until the fringe count is four to five interference bands. The quality of flatness is determined by the straightness of the fringe lines across the wringing surface of the gage block.

Another reading is required to measure twist or high corners on the block. This value is read by positioning the optical flat to one edge and reading the fringes parallel to opposite edge. If no twist is evident, the fringes will be parallel to the edges, otherwise, the fringes will appear as a fan and the interpretation is obtained from reading the deviation form being parallel

Gage blocks smaller than 2.5 mm are not tested for flatness, however they are inspected for surface defects both visually and under a monochromatic light and an optical flat.

d) Temperature normalizing

The temperature of the blocks to be compared must be the same when lengths of the blocks are compared.

Allow a normalizing period of at least one hour and an additional hour for each 25 mm of length up to eight hours; except when abnormal temperature differences exist due to temporary storage or transportation in uncontrolled atmosphere, in which case, an overnight waiting period is appropriate.

e) Procedure

The comparison is carried out as a one to one comparison or as a multi measurement procedure in a least squared design. In a one to one comparison gauge blocks of the same nominal length are compared and the deviation of the block from its nominal value is determined using the value of the known block.

In a least squared design a number of blocks of a set are measured using the comparator and the deviations are determined by multi linear regression.

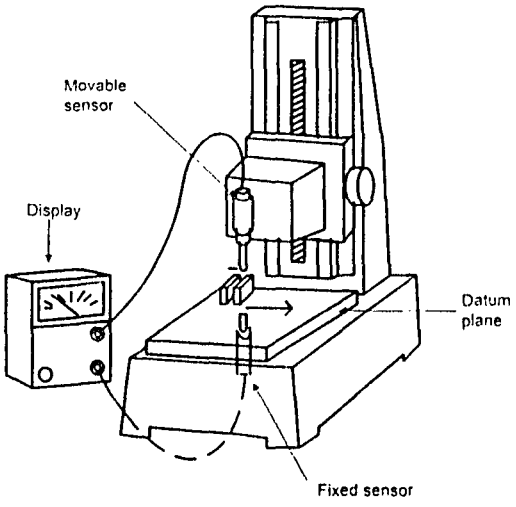


Figure 10.2 Gauge block comparator

f) One to one comparison

In a one to one comparison the test gauge block is compared with a standard gauge block of the same nominal size using a gauge block comparator and the deviations of the test gauge block noted down. Each block is measured at least three times near the center of each datum surface. The measurements are temperature corrected by measuring the temperature of the block using a digital thermometer whose sensor is located on the platen of the comparator or the block itself..

Measurements on 50 mm to 1000mm blocks require special handling techniques to minimize thermal effects. From the known values of the standard blocks, the values of the unknown test blocks are computed.

The temperature of the laboratory is maintained at the reference temperature(usually 20 °C ±1 °C) .

g) Drift-eliminating design for gauge blocks

Calibration designs allow comparison of several gauge blocks of the same nominal size to one standard gauge block in a manner that promotes economy of operation and minimizes wear on the standard gauge. The calibration design is repeated for each size until measurements on all the blocks in the test sets are completed.

Measurements on gauge blocks are subject to drift from heat build-up in the comparator. This drift must be accounted for in the calibration experiment or the lengths assigned to the blocks will be contaminated by the drift term.

Elimination of linear drift

There are a number of designs given by different authors that minimise the effects due to linear drift if the measurements are equally spaced over time. The size of the drift is the average of the n difference measurements. Keeping track of drift from design to design is useful because a marked change from its usual range of values may indicate a problem with the measurement system.

A design using two standard blocks, R_1 and R_2 and two test blocks is given below :

The notation used here, the plus and minus signs, indicate the items entering into the difference measurement. Thus y_2 is a measurement of the difference (D-A).

Definition of master block and check standard

The first two blocks in the design are standard blocks, and are designated A and B, The difference between A and B is used as the check standard.

OBSERVATIONS	A	B	C	D
y_1	+	-	o	o
y_2	-	o	o	+
y_3	o	o	+	-
y_4	o	+	-	o
y_5	o	+	o	-
y_6	-	o	o	+
y_7	+	o	-	o
y_8	o	-	+	o

If we denote the values determined for A, B, C and D by $\hat{A}, \hat{B}, \hat{C}$ and $\hat{D}$ we can write :

$\hat{A} = 1/24\ (5y_1-2y_2-y_3-2y_4-3y_5-2y_6+3y_7+2y_8) + K/2$

$\hat{B} = 1/24\ (-5y_1+2y_2+y_3+2y_4+3y_5+2y_6-3y_7-2y_8) + K/2$

$\hat{C} = 1/24\ (-y_1+2y_2+5y_3-6y_4-y_5+2y_6-7y_7+6y_8) + K/2$

$\hat{D} = 1/24\ (y_1+6y_2-5y_3-2y_4-7y_5+6y_6-y_7+2y_8) + K/2$

$\hat{A} - \hat{B} = 1/24\ (10y_1-4y_2-2y_3-4y_4-6y_5-4y_6+6y_7+4y_8)$

Where $\hat{A} + \hat{B}$ necessarily sum to K.

The standard deviations of the estimated values are given by the following equations:

$s_{\hat{A}} = s_{\hat{B}} = \sigma\sqrt{5/48}$

$s_{\hat{C}} = s_{\hat{D}} = \sigma\sqrt{13/48}$

standard deviation of $\hat{A} - \hat{B}$ is given by $s_{(A-B)} = \sigma\sqrt{5/12}$

The process standard deviation σ is estimated from the standard deviation of the residuals using the equation :

$$\sigma = \sqrt{\frac{\sum (residuals)^2}{4}}$$

with degrees of freedom = 8-5+1=4

10.2.2 End standard rod

a) Reference standard

A linear measuring machine incorporating a secondary standard He-Ne laser interferometer is used to calibrate end standard rods.

b) Procedure

The end standard rod is supported on V blocks on the bed of the measuring machine(See Figure.3.1) The rod is carefully moved until one end is in contact with the anvil of the fixed carriage. The movable carriage is then moved until its anvil is in contact with the other end of the rod. The carriage is locked and the reading displayed by the interferometer is recorded. The procedure is repeated at least three times. The rod is then rotated end to end and a further set of readings is obtained. The readings are corrected for temperature variation from the reference temperature. The average and the standard deviation of the corrected readings are computed.

10.2.3 Ring gauge standard

a) Reference standard

A ring gauge or setting ring is calibrated in a ring gauge calibrator. Two versions of ring gauge calibrators are available, the mechanical comparator type where the ring gauge under calibration is compared with a block of gauge blocks and the comparator of more recent origin where the comparison is against a laser holoscale or grating interferometer. An instrument incorporating a laser holoscale is shown in Figure 10.6.

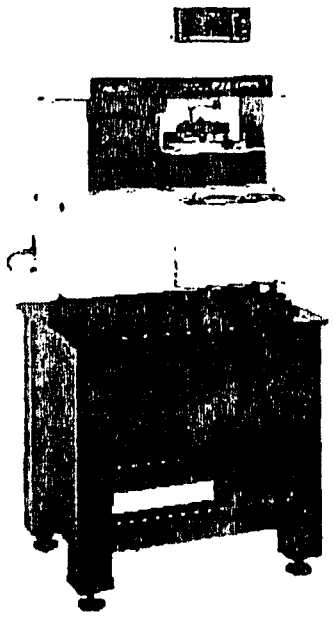


Figure 10.6 Ring gauge calibrator

b) Procedure

A number of diameters of the ring gauge are measured and the mean and the standard deviation are computed. Also the out of roundness or ovality of the ring gauge is estimated.

10.2.4 Surface plate

a) Reference standard

The flatness of a surface plate, i.e the vertical deviations of the surface can be measured using an autocollimator and a small kinematically located mirror, which is moved from point to point on the surface. More recently these measurements are carried out using a He-Ne laser interferometer and a set of movable mirrors and retro reflectors.

b) Procedure

A surface plate is calibrated using a method first described by J.C Moody.(ref xx). The basic procedure is to measure the elevation of the surface at a series of points located on the surface in the form of a grid, Figure 10.7.The elevation measurements are then converted to deviations from a mean plane. The flatness is expressed as the maximum deviation from this mean plane or the separation of two planes encompassing all the measured points of the surface, Figure 10.8.

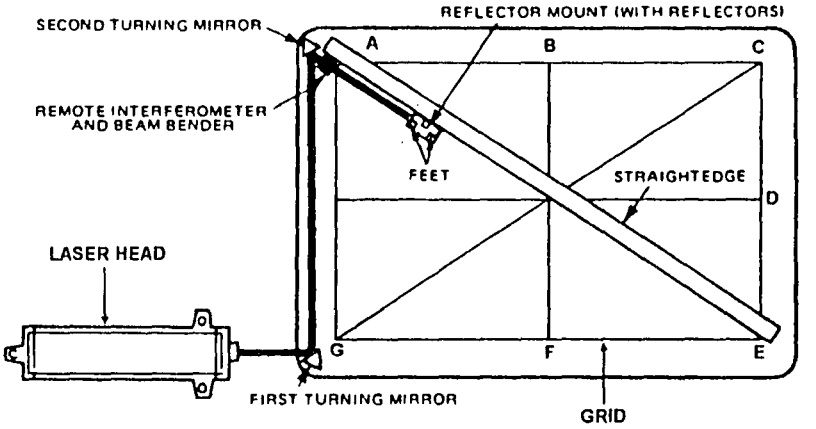


Figure 10.7 – Location of laser interferometer and grid for flatness measurement of a surface plate

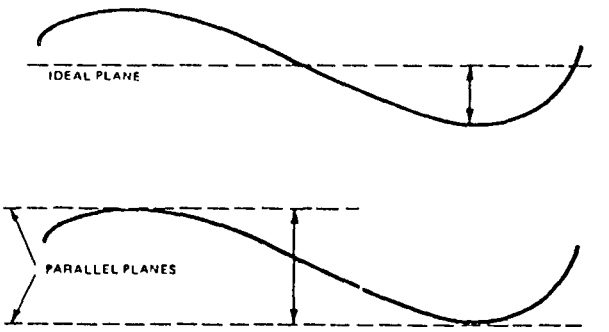


Figure 10.8 – The flatness of a surface

Prior to calibration, the surface plate is cleaned thoroughly and allowed to reach thermal equilibrium withy its surroundings (Several hours to full day). The mechanical accessories of the interferometer to be used for the purpose are also cleaned according to the manufacturer's instructions.

A grid map as shown in Figure 10.7 is drawn on a sheet of paper with highlights located on the surface plate itself with lead pencil, chalk or other suitable marking. The markings should be away from the grid lines allowing the retro reflector to move on the plate surface along these lines. The grid system should have the eight basic lines as shown in Figure 10.7.

The length of each line in the grid must be an even integral multiple of the foot spacing of the retro reflector mount. Otherwise special fixturing is required to perform the calibration. If special foot spacing fixture is used, then a simple proportionality factor is used to convert the readings into true elevation.

The laser head is mounted such that the laser beam is pointed approximately parallel to the perimeter line GE and at least 25 mm outside of the grid. Next a turning mirror is mounted on

the surface plate and the laser head is adjusted until the reflected beam enters the output port of the laser head.

Using two turning mirrors the laser beam can be directed along any line of the grid pattern as shown in Figure 10.9.and elevations of the surface read from the laser display. A complete traverse of the grid is carried out starting from one location and ending at the same location.

Full details of the method are given in reference xx.

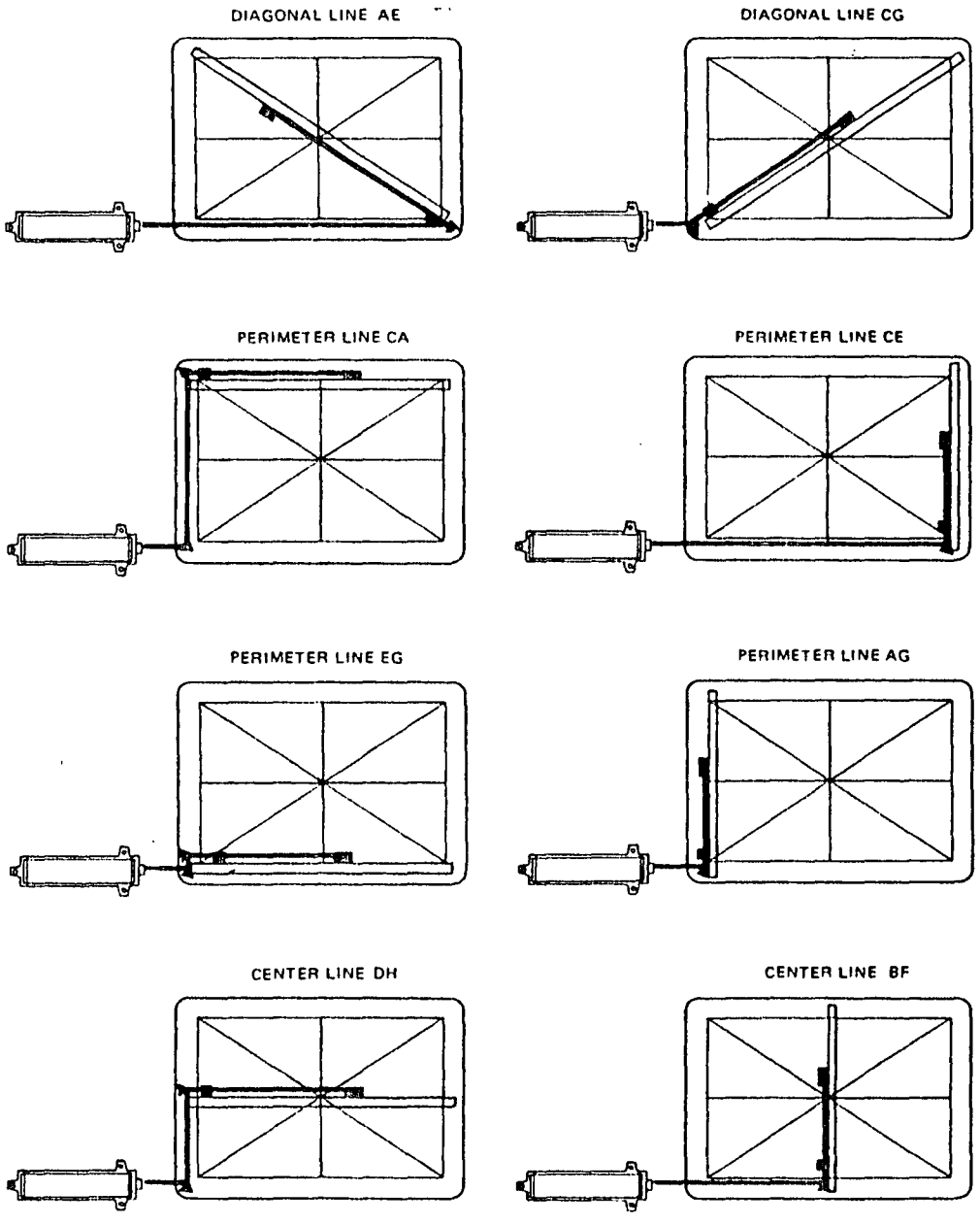


Figure 10.9-Surface plate measurement sequence

10.2.5 Optical flats and parallels

a) Reference standard

The calibration of optical flats and parallels consist of checking them for flatness and parallelism. The flatness is determined against a master optical flat usually mounted in an Fizeau interferometer.

The parallelism of opposite faces is determined using a gauge block comparator shown in Figure 10.2.

b) Flatness measurement

The optical flat is placed on the work table of the interferometer and the master optical flat is brought approximately 6 mm away from the top surface of the test flat.

The work table adjusting screws are adjusted to align the movable image exactly in coincidence with a fixed reference image in the center of the field of view of the interferometer microscope.

The table screws are adjusted to position the fringe pattern parallel to axis A-A' and to obtain the desired number of fringes (normally 4 to 6).

The filar-micrometer of the interferometer is used to determine the largest deviation of the fringe from a straight line in tenths of a fringe, Figure 10.10.

the deviation from flatness is computed by multiplying the number of fringes observed by the wavelength of the monochromatic source used in the interferometer.(Usually 316.4 nanometers for He –Ne laser source)

c) Measurement of Parallelism

The measuring anvils of the comparator are adjusted to the nominal thickness of the optical flat.

Position the optical flat between the comparator measuring anvils to make a measurement at the approximate center. Perform the necessary operations to set the comparator to a zero indication on the display.

Make measurements at points A, A', B, and B' (figure 10.10). Record the maximum deviation obtained as the parallelism of the optical flat.

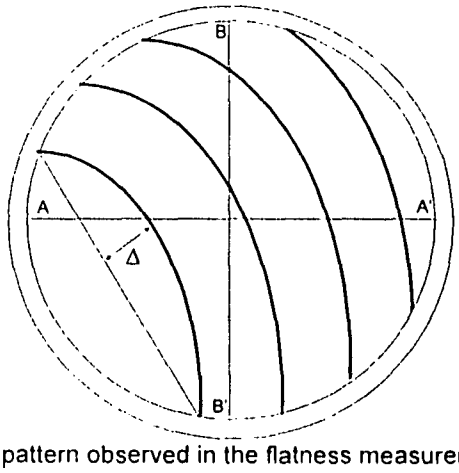


Figure 10.10-Fringe pattern observed in the flatness measurement of an optical flat

10.3 Calibration of instruments

10.3.1 Micrometer

The calibration of a micrometer mainly consists of testing the instrument for accuracy(deviation of reading), flatness and parallelism of measuring faces.In some cases repeatability is also done.

a) Deviation of reading

The deviation of reading of a micrometer over its working range is determined by measuring a set of gauge blocks of appropriate class, usually OIML RI 30 Class B or ISO 3650 Grade 1 or 2, using the micrometer under calibration. The micrometer is firmly held in a rigid stand and the gauge block is introduced between the anvils. The movable anvil is rotated until it comes in contact with the datum surface of the gauge block. The micrometer reading is taken and compared with the actual length of the gauge block, obtained from its calibration certificate. The procedure is repeated at least three times at each major graduation and the mean value of the reading computed.

b) Flatness of measuring faces

An optical flat is used to test the flatness of measuring faces as shown in Figure 6.3. An optical flat of diameter 45 mm or 60 mm is generally used. After cleaning the measuring face of the anvil thoroughly, one surface of the optical flat is brought into contact with the measuring face. Unless the faces are perfectly flat a number of colored interference bands will be seen on their surfaces. The shape and the number of these bands indicate the degree of flatness of the face. A band represents a distance of 0.32 μm.

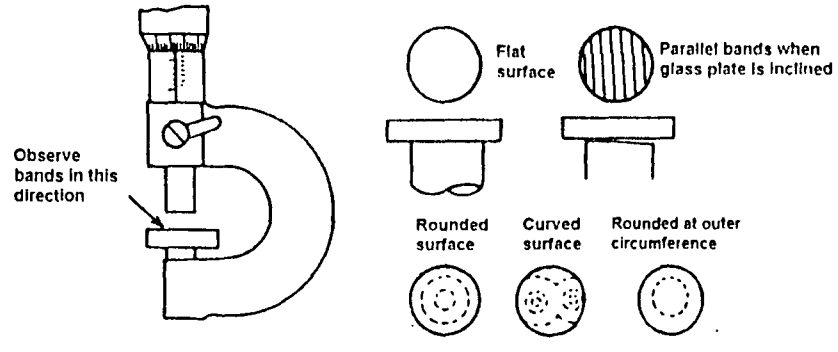


Figure 10.3 –Testing of flatness of a micrometer measuring face

c) Parallelism of measuring faces

Parallelism of measuring faces is determined by either using optical parallels or gauge blocks. Parallelism should be tested at four angular positions of the anvil. For 0-25 mm micrometers, 12.00mm, 12.12 mm, 12.25 mm and 12.37 mm parallels are used.

The optical parallel is first placed on the measuring face of the anvil and carefully moved until the bands visible on the face are reduced to a minimum. The measuring face of the spindle is then brought into contact with the optical parallel. The number of bands visible on both faces gives the parallelism of the measuring faces.

For micrometers of range 50 mm and larger it is more convenient to use gauge blocks. A gauge block is placed at five positions between two measuring faces. The maximum difference of the five readings is considered as the parallelism of the measuring faces. Testing is preferably done at two angular positions of the anvil, by using two gauge blocks differing in length by 0.25 mm.

10.3.2 Vernier caliper

The calibration of a vernier caliper basically consists of the following tests:

a) Deviation of reading

The deviation of reading is determined by the use of gauge blocks or end bars or by the use of a measuring machine. The deviations of reading at not less than five positions, equally spaced within the measuring range of the main scale and the vernier scale are determined.

b) Flatness of the measuring faces

The flatness of the measuring faces for both external and internal measurement is determined either by using a dial test indicator or an optical flat. When a dial test indicator is used, the test instrument is laid horizontally on a surface plate and the tip of the dial test indicator is traversed along the surface of the measuring face. The maximum deviation of the indicator is taken as a measure of flatness. When an optical plate is used, a procedure similar to testing of flatness of the measuring faces of a micrometer is followed.

c) Parallelism of the measuring faces

Parallelism of the measuring faces is determined by inserting gauge blocks at different points on the jaws or by using a measuring machine. Generally parallelism is determined at two measured lengths, mid range and close to full range.

d) Squareness of the fixed face

The squareness of the fixed face for external measurement with the guiding edge of the beam is determined by holding a gauge block of comparable length against the edge of the beam and fixed measuring face.

In addition the thickness of the main scale lines and vernier scale lines are checked by direct measurement using an optical microscope.

10.3.3 Dial gauge

a) Deviation of reading

The deviation of reading of a dial gauge is usually determined using a dial gauge calibrator. A simple design of a dial gauge calibrator is shown in Figure 6.5. The instrument consists of a calibrated micrometer head attached to a fixed vertical column. The dial gauge under test is clamped and held rigidly opposite, and in line with the axis of the micrometer head.

A series of readings is taken at suitable intervals throughout the range of the gauge. If the gauge has only a limited range with two or three turns of its pointer a tenth of the range is a suitable interval. In the case of gauges with longer scales a few intervals in each revolution is tested in order to keep the number of readings within reasonable bounds.

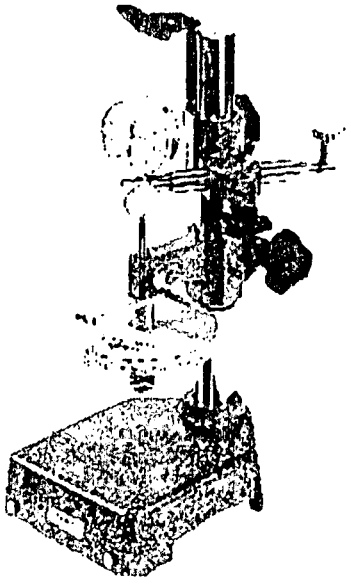


Figure 10.5 – Dial gauge calibrator

b) Repeatability of reading

The repeatability of a dial gauge could be determined in one of two ways. The dial gauge is firmly clamped in a suitable rigid fixture over a flat steel base and a cylinder is rolled under the contact point a number of times from various directions. The test is repeated at two or three points along the range of the gauge.

Alternatively the contact point is allowed to rest on a flat surface below and the plunger is lowered on to the surface both slowly and abruptly. In both cases the largest difference between the readings is noted as the repeatability.

c) Discrimination

Stickiness or backlash of a dial gauge is revealed by the test for discrimination. The dial gauge is mounted in a rigid fixture with the end of its plunger in contact with the surface of a slightly eccentric precision mandrel mounted between centers. A sensitive indicator (e.g. roundness measuring machine) is used beforehand to determine the amount of eccentricity in the mandrel.

11 Calibration of balances and weights

11.1 Calibration of balances

11.1.1 Location and environment

In general balances should be calibrated in situ. i.e. at the place where the balance is operated. This is especially applicable to balances, which measure gravitational force rather than compare masses. The stability of environmental conditions at the place of calibration is also important, especially, the ambient temperature and humidity. Most precision balances are susceptible to changes in temperature and humidity. The stability of the room temperature is very important, though the actual value is relatively unimportant, The temperature of the balance room should not change by more than ± 2 °C (or 3 °C) during any eight hour period.

Air currents and dust level in the atmosphere may also be influencing factors. Draught shields are essential for reasonably precise weighing as air currents can cause errors of several parts per million. Other influence factors of importance are strong magnetic or electro-magnetic fields that may affect mechanical components or electronics of the balance.

11.1.2 Reference standard

Balances are calibrated using standard masses of known conventional value and uncertainty. The combined uncertainty of the standard masses used for the calibration should at least be less than one third of the specified or expected uncertainty of the balance under calibration. The masses should also have traceability to the international system with valid calibration certificates. The hierarchy of mass standards for balance calibration is given in Figure 11.1.

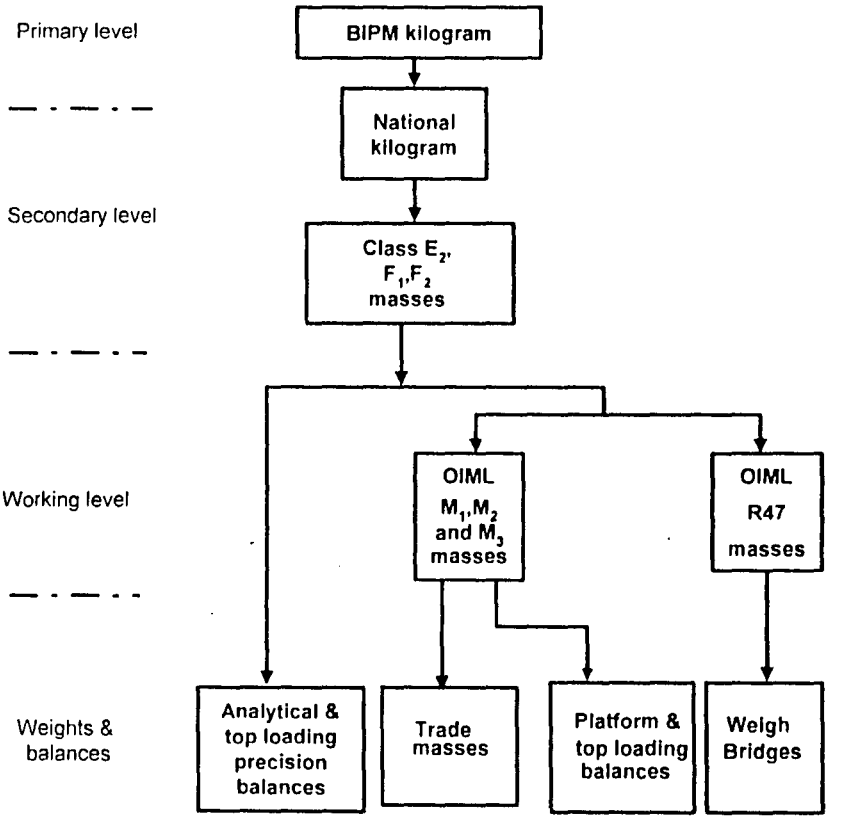


Figure 11.1 Calibration hierarchy for balances

11.1.3 Calibration parameters

The parameters of calibration depend on the type of balance. As the most common precision balance type in present day use, is the direct reading electronic type, a brief outline of the calibration procedure of this type of balance is given.

11.2 Calibration of direct reading electronic precision balances

The main parameters which are tested in the process of calibration of this type of balance are scale value, linearity, repeatability, off center loading effect and hysteresis. To carry out the tests given in this section the balance should have reached equilibrium with its environment. This means that the balance should have been switched on for a considerable period of time before carrying out the tests. Usually an hour or two is added to the manufacturer's recommendation.

11.2.1 Levelling

Most balances are provided with a level indicator and the balance should be carefully levelled before calibration (and use). The level should be checked from time to time and whenever the balance has been moved.

11.2.2 Scale value

Setting scale value is the process of establishing the correspondence between the mass units indicated in the display and the sensing parameter of the balance. i.e. electric current or voltage.

In some direct reading balances an in-built calibration mass is incorporated for this purpose and when the balance is switched on or when the calibration procedure is activated this mass is used automatically to set the scale value. In a majority of the balances an external mass close to the maximum capacity has to be used for setting the scale value. The procedure given in the technical manual of the balance should be followed in carrying out this operation.

The external mass has to be chosen carefully. The deviation of the mass from its nominal value should be less than half the discrimination of the balance if the scale value is to be set near the maximum capacity. If the scale value is to be set at a point less than its maximum capacity then the permissible deviation for the mass is reduced proportionately.

For example a balance with a maximum capacity of 20 kg has a resolution of 0.1 g . The balance calibration is to be carried out using a mass of 20 kg nominal value. The deviation of the 20 kg mass should not exceed ± 50 mg. If the operation is to be carried out at a 10 kg load, then the 10 kg mass used should have a deviation of less than ±25 mg. Reference to Table 4.1(Chapter 4) will indicate that in both cases a mass of Class E2 is required to set the scale value of the balance.

11.2.3 Repeatability

Repeatability is usually determined at half range and full range of the balance.

a) Procedure

Switch on and allow the balance to warm up for the time period recommended in the technical manual of the balance.

1. Choose a mass equal to approximately half the range of the balance.

2. Read zero and record , z_i
3. Place the mass on the pan and record the reading, r_i, remove the mass.
4. Repeat steps 2 & 3, 10 times and record the results.
5. Repeat steps 2,3 and 4 using a mass approx. equal to the full range of the balance.

Tabulate results as shown in Table 11.1 and calculate the standard deviation (s) of the corrected readings from the equation :

$$S = \sqrt{\frac{\sum_{i=1}^{n}(r_i - \bar{r})}{n-1}} \qquad (11.1)$$

where,r is the mean value of the corrected readings r_i and n is the number of observations.

Table 11.1 –Results of repeatability test

Number	Zero(z_i) g	Reading(r_i) g	Difference g
1	0.01	200.01	200.00
2	0.00	200.00	200.00
3	0.02	200.02	200.00
4	0.00	200.01	200.01
5	0.00	200.00	200.00
6	0.01	200.01	200.00
7	0.00	200.01	200.01
8	0.01	200.00	199.99
9	0.02	200.01	199.99
10	0.01	200.02	200.01
	Standard deviation, g		0.01

11.2.4 Linearity

Linearity is a measure of the deviation of the balance reading from the expected value. A set of calibrated masses with known conventional values and uncertainties is required to carry out the linearity test. A procedure often used is given below :

a) Procedure

The balance is tested at ten test points over its working range.

Switch on and allow the balance to warm up for the time period recommended in the technical manual of the balance. Divide the full range of the balance into ten equal steps. e.g. if the balance has a range of 200 g , each step will equal 20 g. Choose a set of weights having known values, which can cover the full range of the balance. Proceed as follows :

1. Read and record the reading (zero)
2. Place a known mass M on the pan and record reading, r_1. Remove the mass.
3. Replace the mass and record the reading, r_2.
4. Remove the mass, record the reading (zero).
5. Repeat steps 2 to 4 for all the test points.
6. Tabulate and calculate results as shown in Table 11.2.

Table 11.2 Results of linearity test

Pan load g	Balance reading g	Mean g	Corr. balance reading g	Value of standard mass g	Correction g
0 20 20	0.00 20.01 20.02	0.00 20.02	20.02	19.99	-0.03
0 40 40	0.00 40.00 40.01	0.00 40.01	40.01	9.99	-0.01
0 60 60	0.00 60.02 60.02	0.00 60.02	60.02	60.01	-0.01
0 80 80	0.00 80.02 80.01	0.01 80.02	80.01	80.01	0.00
0 100 100	0.01 100.01 100.00	0.01 100.01	100.00	99.99	-0.01
0 120 120	0.00 120.02 120.01	0.00 120.02	120.02	120.00	-0.02
0 140 140	0.00 140.00 140.01	0.01 140.01	140.00	139.99	-0.01
0 160 160	0.01 160.01 160.01	0.01 160.01	160.00	160.01	0.01
0 180 180	0.01 180.00 180.01	0.01 180.01	180.00	180.01	0.01
0 200 200 0	0.00 200.00 200.01 0.00	0.00 200.01	200.01	200.01	0.00

11.2.5 Off center loading effect

The off-center load error occurs, when the center of mass of the object being weighed is off – centre on the pan. The test is done at the load recommended by the manufacturer of the balance (Usually 1/3 or ½ the range of the balance).

a) Procedure

1. Switch on the balance and allow it to warm up for the time period recommended in the technical manual.
2. Choose a mass about 1/3 or ½ the full range of the balance.
3. For balances upto 10 kg use an Aluminium or Perspex disc of 50 mm diameter .For balances of higher capacity the disc is not required.
4. Place the mass centrally on the disc (if used) and place the disc or the mass on the center of the pan. Record the reading r_c.
5. Move the disk (or the mass) to the left,back,right and front edges of the pan and record readings r_l, r_b, r_r, and r_f respectively.

Calculate the maximum difference between the readings as the effect of off-center loading as shown in Table 11.3.

Table 11.3 – Results of off center loading test

A mass of 100 g is placed on a disk of 50 mm diameter and moved to various positions on the pan. The balance readings obtained are given in the Table.

Centre r_c	Front r_f	Back r_b	Left r_l	Right r_r	Maximum difference g
107.18	107.20	107.17	107.18	107.19	0.03

11.2.6 Hysteresis

a) Procedure

Proceed as follows :

1. Switch on the balance and allow it to warm up for the time period recommended in the technical manual of the balance.
2. Zero the balance and record the reading, z_1.
3. Place a mass M, equal to half the range on the pan, m_1
4. Add extra mass to bring the balance reading close to full range.
5. Remove the extra mass and read the balance with M still on the pan, m_2.
6. Remove M and read and record zero, z_2.
7. Repeat the above procedure three times and average the differences $(m_1 - m_2)$ and (z_1-z_2).
8. Hysteresis of the balance = higher of $(m_1 - m_2)$ or (z_1-z_2)

   (Note : Some recent publications define hysteresis as the average of $(m_1 - m_2)$ *and* (z_1-z_2)*).*

Table 11.4 Results of hysteresis test

Half capacity of balance = 100 g				
Pan load		**Run 1**	**Run 2**	**Run 3**
Zero	z_1	0.00	0.00	0.00
M	r_1	100.03	100.03	100.03
M+M'		200.04	200.04	200.04
M	r_2	100.02	100.02	100.02
Zero	z_2	0.00	0.00	0.00
Calculations :				
z_1-z_2		0.00	0.00	0.00
r_1-r_2		0.01	0.01	0.01

11.3 Calibration of weights

11.3.1 Handling of weights

Weights of Class E and F should never be touched with bare hands. The large weights are handled using clean gloves (chamois, cotton or plastic) or with a lifting tool. Small weights should be handled with bone or plastic tipped tweezers. In the case of precise measurements, putting hands inside the balance case for loading and unloading of the weights should be avoided, as this can generate air currents and temperature effects. To avoid the problems of hand-heating, long-handled weight lifting devices should be used wherever possible for prcise weighing.

11.3.2 Care of weights

The following guidelines should be followed :

a) When not in use the weights should always be kept in the box or container provided.

b) Weights from two or more sets should not be mixed.

c) Weights should never be dropped; if dropped they must be recalibrated.

d) Weights should never be placed on dusty or dirty surface, or slide across a surface, especially on a balance pan.

e) Weights should not be allowed to clink together. Sometimes it may be necessary for them to touch when a few on a pan, but this should be done carefully.

f) Weights should not be cleaned with solvent unless absolutely necessary. If they are too dirty and cleaning with solvent is reqüired sufficient time should be allowed for the weights to settle before use Typical stabilization times after cleaning are given in OIML R 111.

g) For any calibration involving weights, they should be in thermal equilibrium with the ambient conditions in the laboratory, and with the balances as well for E1 to F1 calibrations. The times required for temperature equalisation are given in OIML R 111.

11.3.3 Weighing methods

Accurate calibrations of weights are always done by comparing the test weight with a known standard weight or a group of standard weights. For this purpose a variety of weighing methods are available. The most common methods are single substitution weighing, double substitution weighing and transposition weighing (in the case of equal arm balances).

a) Single substitution weighing

For single substitution weighing either an equal arm balance or a single pan balance (electronic comparator, top loading or two knife edge types) could be used. The procedure is as follows:

1. Place the unknown weight (X) on the pan and record reading t_1.

   (In the case of an equal arm balance, place the unknown weight on one pan and place a weight (W) which will counter balance the unknown weight on the other pan).

2. Replace the unknown weight with a known standard weight (S).Record reading r_1.

3. Add an accurately known sensitivity weight (δm) to the pan containing S. Record reading r_2.

The value of the unknown weight is obtained from the equation :

$$M_X = M_S + \frac{m_s(t_1 - r_1)}{(r_2 - r_1)} \qquad (11.2)$$

where M_X -Mass value of X,

M_S - Mass value of S,

m_s -Mass value of sensitivity weight

b) Double substitution weighing

A more accurate method is double substitution weighing. The steps are as given below:

Step	Load on balance	Reading
1	X	t_1
2	S	r_1
3	S + m_s	r_2
4	X + m_s	t_2

The unknown mass value M_X is given by :

$$M_X = M_S + \frac{m_s(t_1 + t_2 - r_1 - r_2)}{2(r_2 - r_1)} \qquad (11.3)$$

c) Extended substitution weighing

Extended substitution weighing consists of repeating a double substitution weighing two or more times to give the readings :

t_1 r_1 r_2 t_2

t_3 r_3 r_4 t_4

t_5 r_5 r_6 t_6

The unknown mass value M_X is given by :

$$M_X = M_R + \frac{m_s}{n} \sum_{i=1}^{n} \frac{(t_i - r_i)}{(r_{i+1} - r_i)} \qquad (11.4)$$

where n is an even number.

d) Sensitivity weight

The purpose of using a sensitivity weight is to determine the constant of proportionality (k in weighing equation, (see Section 11.4.1) of the balance as the weighing operation is being carried out.

The accurate value of the sensitivity weight and its uncertainty should be known. Also the value of the weight should be such that the balance rest position is within the readable scale (particularly for equal arm balances).

11.3.4 Calibration of weights by direct comparison weighing

A direct comparison weighing is carried out when a single weight is required to be calibrated. The test weight is compared with a standard weight either by single substitution. double substitution or extended substitution method. The choice of the weighing is dependent on the desired uncertainty of the mass value of the test weight. In most cases a double substitution procedure is sufficient.

11.3.5 Calibration of weights using weighing designs (least squared designs)

Weighing designs are used when more than one weight has to be calibrated. Usually weighing designs are designed for calibration of sets of weights having weights denominated in decades.

The method is illustrated using an example decade weighing design. A weight set containing the following weights is to be calibrated :

500 g, 200 g, 200 g, 100 g

The calibration is based on one 1 kg standard weight designated S, and a 100 g check standard weight designated 100C.The check standard weight is incorporated in the design to test for the reliability of the calibration.

a) Weighings:

The weighings are represented by the following equations. Each equation represents a weighing operation carried out by double substitution weighing. The quantities a, b, c, d, e, f, g and h are experimental values obtained from each weighing operation using equation (11.3).

$$\begin{aligned}
500 + 200 + 200' + 100 &= S + a \\
500 + 200 + 200' + 100\,C &= S + b \\
500 - 200 - 200' - 100\,C &= c \\
500 - 200 - 200' - 100 &= d \\
200 - 200' &= e \\
200' - 100 - 100\,C &= f \\
200 - 100 - 100\,C &= g \\
100 - 100\,C &= h
\end{aligned} \qquad (11.5)$$

$$a = \frac{m_s(t_1 + t_2 - r_1 - r_2)}{2(r_2 - r_1)} \qquad (11.6)$$

In this equation t_1 and t_2 are the readings obtained when the group of weights 500, 200, 200'and 100 g are weighed. Similarly r_1 and r_2 are the balance readings when the standard weight S is weighed in the double substitution weighing scheme.

b)Sum of squares :

The residuals are squared and added to obtain the sum of squares as given in the following equation:

$$\mathbf{SS} = (500 + 200 + 200' + 100 - S - a)^2 + (500 + 200 + 200' + 100\,C - S - b)^2 + (500 - 200 - 200' - 100C - c)^2 + (500 - 200 - 200' - 100 - d)^2 + (200 - 200' - e)^2 + (200' - 100 - 100C - f)^2 + (200 - 100 - 100C - g)^2 + (100 - 100C - h)^2 \qquad (11.7)$$

In the least squares method the sum of squares is minimised. This is done by differentiating the **SS** with respect to each unknown and equating the resulting partial differential co-efficients to zero. The resulting set of equations is known as Normal equations. I.e.

$$\left[\frac{\partial SS}{\partial 500}\right] = \left[\frac{\partial SS}{\partial 200}\right] = \left[\frac{\partial SS}{\partial 200'}\right] = \left[\frac{\partial SS}{\partial 100}\right] = \left[\frac{\partial SS}{\partial 100C}\right] = 0 \qquad (11.8)$$

c) Normal equations:

The normal equations are given below :

$$\begin{aligned}
4(500) + 0(200) + 0(200') + 0(100) + 0(100\,C) &= 2S + a + b + c + d \\
0(500) + 6(200) + 3(200l) + 1(100) + 1(100\,C) &= 2S + a + b - c - d + e + g \\
0(500) + 3(200) + 6(200') + 1(100) + 1(100\,C) &= 2S + a + b - c - d - e + f \qquad (11.9) \\
0(500).+ 1(200) + 1(2001) + 5(100) + 1(100\,C) &= S + a - d - f - g + h \\
0(500) + 1(200) + 1(2001) + 1(100) + 5(100\,C) &= S + b - c - f - g - h
\end{aligned}$$

d) Solution:

By solving the five simultaneous equations the solution is obtained as :

$$\begin{aligned}
500 &= S/2 + 1/4\,(a + b + c + d) \\
200 &= S/5 + 1/30(3a + 3b - 3c. - 3d + 10e - 2f + .8g) \\
200' &= S/5 + 1130(3a + 3b - 3c - 3d - 10e + 8f - 2g) \qquad (11.10) \\
100 &= S/10 + 1/40(7a - 3b + 3c - 7d - 8f - 8g + 10h) \\
100C &= S110 + 1/40(-3a + 7b - 7c + 3d - 8f - 8g - 10h)
\end{aligned}$$

11.3.6 Matrix solution

The set of equations (11.5) can be written in matrix form as,

$$\begin{pmatrix}
1 & 1 & 1 & 1 & 0 \\
1 & 1 & 1 & 0 & 1 \\
1 & -1 & -1 & 0 & -1 \\
1 & -1 & -1 & -1 & 0 \\
0 & 1 & -1 & 0 & 0 \\
0 & 0 & 1 & -1 & -1 \\
0 & 1 & 0 & -1 & -1 \\
0 & 0 & 0 & 1 & -1
\end{pmatrix}
\begin{pmatrix}
500 \\ 200 \\ 200' \\ 100 \\ 100C
\end{pmatrix}
=
\begin{pmatrix}
S+a \\ S+b \\ c \\ d \\ e \\ f \\ g \\ h
\end{pmatrix}$$

(11.11)

A . M

A . M = X

The solution is given by $M = (A^T.A)^{-1}.A^T.X$, (11.12)

where ,

A^T – Transpose of matrix A,

$(A^T.A)^{-1}$ _ Inverse of matrix $(A^T.A)$

Computation of the right hand side of the equation (11.12) gives the solution :

$$
\begin{aligned}
500 &= S/2 + 1/4\,(a + b + c + d) \\
200 &= S/5 + 1/30(3a + 3b - 3c. - 3d + 10e\text{-}2f + .8g) \\
200' &= S/5 + 1130(3a + 3b - 3c - 3d\text{-}10e + 8f - 2g) \\
100 &= S/10 + 1/40(7a - 3b + 3c - 7d - 8f - 8g + 10h) \\
100C &= S110 + 1/40(-3a + 7b - 7c + 3d - 8f - 8g - 10h)
\end{aligned}
\qquad (11.13)
$$

which is the same solution as given above.

a) Variance –Covariance matrix

The Type A standard uncertainties of the resulting mass values are obtained by taking the square root of the diagonal values of the variance covariance matrix given below:

$$
SS \times \begin{pmatrix}
0.25 & 0 & 0 & 0 & 0 \\
0 & 0.227 & -0.107 & -0.02 & -0.02 \\
0 & -0.107 & 0.227 & -0.02 & -0.02 \\
0 & -0.02 & -0.02 & 0.215 & -0.035 \\
0 & -0.02 & -0.02 & -0.035 & 0.215
\end{pmatrix}
$$

Thus,

$$U_A^{500} = \sqrt{Var(500)} = \sqrt{SS \times 0.25}$$

$$U_A^{200} = \sqrt{Var(200)} = \sqrt{SS \times 0.227}$$

$$U_A^{200'} = \sqrt{Var(200')} = \sqrt{SS \times 0.227} \qquad (11.14)$$

$$U_A^{100} = \sqrt{Var(100)} = \sqrt{SS \times 0.215}$$

$$U_A^{100C} = \sqrt{Var(100C)} = \sqrt{SS \times 0.215}$$

The method of calculating the combined standard uncertainty of the mass values is explained in Chapter 9.

11.4 True Mass, Apparent Mass and Conventional Mass

11.4.1 True Mass (Vacuum Mass)

True mass of an object is the mass as defined by equation (4.1). If the mass of an object is determined by weighing it in a vacuum, the mass obtained will be identical to that obtained using equation (4.1). Due to this reason "True mass" is also known as " Vacuum mass". However, weighing in vacuum is rarely carried out though the concept is very useful to explain mass measurement procedures.

11.4.2 The weighing equation

If two masses, M_1 and M_2 having 'True Mass' values of M_1^T and M_2^T are compared using a balance, the following equation can be written:

$$M_1^T - M_2^T = k.(\theta_1 - \theta_2) + \rho_a (V_1 - V_2) \qquad (11.15)$$

In this equation,

k - factor for converting balance deflections to mass values (sensitivity)

θ_1, θ_2 - deflections of the balance corresponding to masses M_1 & M_2 respectively.

ρ_a - the density of air in which the weighing is carried out.

V_1 , V_2 - the volumes of the masses M_1 and M_2

If ρ_1 and ρ_2 are the densities of the two masses, then

$$\rho_1 = \frac{M_1^T}{V_1}$$

$$\rho_2 = \frac{M_2^T}{V_2} \qquad (11.16)$$

Equation (11.15) can then be written as,

$$M_1^T - M_2^T = k.\Delta\theta + \rho_a \left(\frac{M_1^T}{\rho_1} - \frac{M_2^T}{\rho_2} \right) \qquad (11.17)$$

Where $\Delta\theta = \theta_1 - \theta_2$

It can be seen from equation (11.15) that,

$M_1^T - M_2^T = k.\Delta\theta$ if

$\rho_a.(V_1 - V_2) = 0$ (11.18)

i. e., either

$\rho a = 0$ or

$V_1 - V_2 = 0$

In practical metrology the condition $\rho a = 0$, i.e. weighing in vacuum is only rarely encountered. However the second condition , namely $V_1 = V_2$ is achieved in very many cases when the two masses being compared are nearly equal and the masses are made from the same material of density ρ.

The term $\rho a\ (V_1 - V_2)$ in equation (11.15) is known as the buoyancy correction and could be neglected only if the above conditions are met with. In all other cases, the 'buoyancy correction' should be evaluated to ascertain whether it is significant in comparison to the uncertainty to be achieved in the calibration.

11.4.3 Apparent Mass

The need to apply buoyancy corrections to mass values led to the adoption of the concept of *apparent mass* :

> *The apparent mass of an object X is defined as the true mass of a reference material which will produce a balance reading equal to that produced by the object X when the measurements are done in air of reference density (ρ_0) at specified reference conditions.*

Using equation (11.15),

$$M_X^T - M_R^T = k.\Delta\theta + \rho 0\,(V_X - V_R) \qquad (11.19)$$

Where

M_X^T - true mass of the object X.

M_R^T - true mass of the reference mass R.

V_X - volume of X.

V_R - volume of R.

In density notation, the above equation becomes

$$M_X^T - M_R^T = k.\Delta\theta + \rho 0 \left(\frac{M_X^T}{\rho X} - \frac{M_R^T}{\rho R}\right) \qquad (11.20)$$

Since the readings of both weighings are equal (by definition) $\Delta\theta = 0$, and by definition

$$M_x^A = M_R^T$$

rearranging equation (11.20) gives,

$$M_X^A = M_X^T \frac{(1 - \frac{\rho_0}{\rho_X})}{(1 - \frac{\rho_0}{\rho_R})} \qquad (11.21)$$

Where M_X^A is the apparent mass of the object X at specified reference conditions, i.e. ρ_0 and ρR.

11.4.4 Reference Systems

Two reference systems are used for designating Apparent Masses.

a) The 8.0 System

In this system,

$$\rho_R = 8000 \text{ kg/m}^3 \text{ at } 20^\circ\text{C}$$

$$\rho_o = 1.2 \text{ kg/m}^3 \text{ at } 20^\circ\text{C}$$

and the temperature, $t_o = 20^\circ\text{C}$

Thus in the '8.0 System', equation (11.10) becomes

$$M_X^A = \frac{M_X^T\left[1 - \frac{1.2}{\rho_x}\right]}{\left[1 - \frac{1.2}{8000}\right]}$$

$$M_X^8 = 1.000150023 M_X^T\left[1 - \frac{1.2}{\rho_x}\right] \qquad (11.22)$$

b) The 8.4 System

In the 8.4 system,

$\rho_R = 8400 \text{ kg/m}^3$ at 0°C

$\rho_o = 1.2 \text{ kg/m}^3$ at 20°C

$a = 5.4 \times 10^{-5}$ /°C = Coefficient of cubical expansion of brass

and ρ_R at 20°C, $\rho_{R2\theta} = 8390.938 \text{ kg/m}^3$

substituting the above values in equation (11.21) gives,

$$M_X^{8.4} = 1.00143032\left[1 - \frac{1.2}{\rho_x}\right] \qquad (11.23)$$

Dividing (11.22) by (11.23)

$$M_X^8 = M_X^{8.4} \times 1.00000699 \qquad (11.24)$$

equation (11.24) can be used to convert Apparent Mass values from one system to the other.

11.4.5 Conventional mass value

The conventional mass value of an object is a specific Apparent Mass, where the density of the reference material and the density of air are defined to be 8000 kg/m^3 and 1.2 kg/m^3 at 20 ° C respectively. (OIML RI 33 – Conventional Value of the result of weighing in air).It can be seen that the reference conditions of the 8.0 system are identical to those of the conventional mass definition.

11.4.6 Buoyancy corrections

Buoyancy corrections are required,

a) When the density of the material of construction of the test weight is different to that of the standard masses used in the calibration and,

b) When high precision is required in the calibration process (usually a relative uncertainty of less than $1x10^{-4}$ requires buoyancy corrections).

An important relationship is where an unknown mass of known density or volume is balanced against a standard weight of known conventional mass value under measured atmospheric conditions. In certain cases a buoyancy correction is necessary to determine the conventional value of the unknown mass. The correction δm is given by :

$$\delta m = m_S\left[\frac{1}{d_X} - \frac{1}{8000}\right](d_a - 1.2) \qquad (11.25)$$

where m_s – conventional mass value of the standard weight

d_X - density of the unknown mass

d_a - density of air at the time of the weighing

Example 1: A test mass of nominal value 500 g and density 7800 kg/m^3 is compared with a standard mass having a conventional mass value of 500.125 g in a laboratory with air density of 1. 31 kg/m^3. Determine the buoyancy correction applicable to the conventional mass value of the test mass.

Applying the above equation we get,

$$\delta m = 500.125\left[\frac{1}{7800} - \frac{1}{8000}\right](1.31 - 1.2)$$

δm = 0.000165 g or 0.165 mg.

Example 2 : In a chemical test laboratory a substance having a density of 4300 kg/m^3 is weighed on a weighing balance calibrated using standard masses having a density of 8000 kg/m^3 and conventional mass values referenced to standard air density i.e. 1.2 kg/m^3. The mass indicated on the balance is 200.256 g .

Determine the buoyancy correction that should be applied to the weighing result.

Equation (11.7) could be used to estimate the buoyancy correction in this case as well. However the value of the air density of the environment in which the balance is located is required.

Assuming the air density of the laboratory to be 1.31 kg/m^3 we proceed as follows:

$$\delta m = 200.256\left[\frac{1}{4300} - \frac{1}{8000}\right](1.31 - 1.2) = 0.00231 \text{ g} = 2.31 \text{ mg}$$

Thus 2.31 mg should be added to the weighing result of 200.256 g to obtain the corrected mass of the weighed material. If the required weighing uncertainty is less than ± 0.001 g (1 mg) the buoyancy correction is definitely required.

11.4.7 Errors due to non-correction for buoyancy

The relative error arising from neglecting buoyancy corrections is given by,

$$\delta = \frac{\varepsilon}{MT_X} = \frac{\rho_a(\rho_s - \rho_x)}{\rho_s(\rho_x - \rho_a)} \qquad (11.26)$$

If δ is to be smaller by one order than the uncertainty of calibration ,then $\delta \leq U/10$, which gives :

$$\frac{\rho_s}{\rho_x} < \frac{(1+\frac{U\rho_a}{10.\rho_a})}{(1+\frac{U}{10})} \qquad (11.27)$$

Example 1:

A 1 kg brass mass of density 8500 kg/m^3 is calibrated using stainless steel standard masses of density 7900 kg/m^3. The air density at the time of the weighing was 1.2 kg/m^3. Determine the error that would result if buoyancy corrections were neglected.

From equation (11.26)

$$\delta = \frac{1.2\ (7900 - 8500)}{7900\ (8500 - 1.2)}$$

= -0.000011 or 11 mg in absolute terms.

Example 2:

Determine the limiting density of an object that can be calibrated using standard masses of density 7900 kg/m^3 with relative uncertainties of 1x 10 $^{-6}$ and 1x 10^{-3} if the error due to buoyancy correction was to be less than one tenth of the uncertainty.

From equation (11.27) and neglecting the term U/10 in the denominator in comparison to 1, for

U= 1x10 -6

$$\frac{\rho_S}{\rho_X} < 1 + \frac{10^{-6} \times 7900}{10 \times 1.2} = 1.0007$$

$$\frac{\rho_X}{\rho_S} > 0.9993$$

$$\rho_S - \rho_X < 0.0007\rho_S = 5.5\ \text{kg/m}^3$$

The difference between the densities of the unknown mass and the standard mass should not exceed 5.5 kg/m^3. A similar computation when U=1x 10^{-3} results in,

$$\rho_S - \rho_X < 0.397\rho_S = 3136\ \text{kg/m}^3$$

This shows that when the required uncertainty of calibration is relatively large, the permissible difference of densities between the test object and the standard mass is also comparatively large.

In all cases equation (11.26) should be used to estimate the error that may result due to non correction for buoyancy and determine whether it is significant in comparison to the required uncertainty.

11.4.8 Estimation of air density

Air density of the balance room is required in order to calculate buoyancy corrections. Most national laboratories use an equation proposed by R.S Davies. The equation is known as the 1981/91 equation for the determination of the density of moist air. The equation in simplified form is given below:

$$\rho = \frac{pM_a}{ZRT}\left[1 - x_v\left(1 - \frac{M_v}{M_a}\right)\right] \qquad (11.28)$$

In this equation,

P - the atmospheric pressure ,

T –the thermodynamic temperature,

X_v -the mole fraction of water vapour,

M_a –the molar mass of dry air,

M_v -the molar mass of water ,

R -the gas constant and

Z -the compressibility factor.

Ma is given by the equation :

$$M_a = \left[28.9635 + 12.011(x_{co_2} - 0.0004)\right] \times 10^{-3} \text{kg/mol} \qquad (11.29)$$

where X_{co2} is the mole fraction of carbon dioxide in atmospheric air.The mole fraction of water vapour X_v is obtained from the equation :

$$x_v = hf(p,t)\frac{p_{sv}(t)}{p} \qquad (11.30)$$

where ,

h is the relative humidity of atmospheric air, f(p,t) the enhancement factor and p_{sv} the saturation vapour pressure of moist air. f(p,t) and p_{sv} are obtained from the following equations :

$$f(p,t) = \alpha + \beta p + \gamma t^2 \qquad (11.31)$$

where t is the temperature in degree Celsius,

$$p_{sv} = \text{Exp}\left(AT^2 + BT + C + \frac{D}{T}\right) \qquad (11.32)$$

Finally the compressibility Z is calculated from the following equation :

$$Z = 1 - \frac{p}{T}\left[a_o + a_1 t + a_2 t^2 + (b_o + b_1 t)x_v + (c_o + c_1 t)x_v^2\right] + \frac{p^2}{T^2}(d + ex_v^2) \qquad (11.33)$$

The constant parameters used in the above equations are given in Table 11.5

11.4.9 Approximate equation for estimation of air density

The most accurate formula for estimation of air density is the CIPM formula (1981/91).An approximate formula which may be used is given below :

$$\rho_a = \frac{0.34848p - 0.009024rh \times \exp(0.061t)}{273.15 + t} \qquad (11.34)$$

where,

p - Pressure in mbar (or hPa),

rh – Relative humidity expressed as a fraction,

t - Temperature in °C.

Table 11.5 Values of constant parameters of the CIPM 1981/91 equation

Constant	Value
Vapour pressure at saturation	
A	1.237 884 7 x10^{-5} K^{-2}
B	-1.912 131 6 x 10^{-2} K^{-1}
C	33.937 110 47
D	-6.343 164 5 x 10^{3} K
Enhancement factor	
α	1.000 62
β	3.14 x 10^{-8} Pa^{-1}
γ	5.6 x 10^{-7} K^{-2}
Compressibility factor Z	
a_o	1.581 23 x 10^{-6} K Pa^{-1}
a_1	-2.9331 x 10^{-8} Pa^{-1}
a_2	1.1043 x10^{-10} $K^{-1}Pa^{-1}$
b_o	5.707 x 10^{-6} K Pa^{-1}
b_1	-2.051 x 10^{-8} Pa^{-1}
c_o	1.9898 x 10^{-4} K Pa^{-1}
c_1	-2.376 x 10^{-6} Pa^{-1}
d	1.83 x 10^{-11} K^2 Pa^{-2}
e	-0.765 x 10^{-8} K^2 Pa^{-2}
Gas constant R	
R	510 J mol^{-1} K^{-1}
Leading constant	
Ma/R (x_{co2}=0.000 4)	3.483 49 x 10^{-3} kg K J^{-1}

12 Calibration of pressure standards and instruments

12.1 Essential features

The most important general concepts relating to calibration of pressure standards and measuring instruments are discussed in this section.

12.1.1 Reference standard

The hierarchy of pressure measurement standards is given in Figure 12.1, which may be used for selection of the next higher level standard for the calibration of a particular standard or instrument. However the traceability path given in this diagram is not the only possible solution. What is indicated is one of many possible solutions.

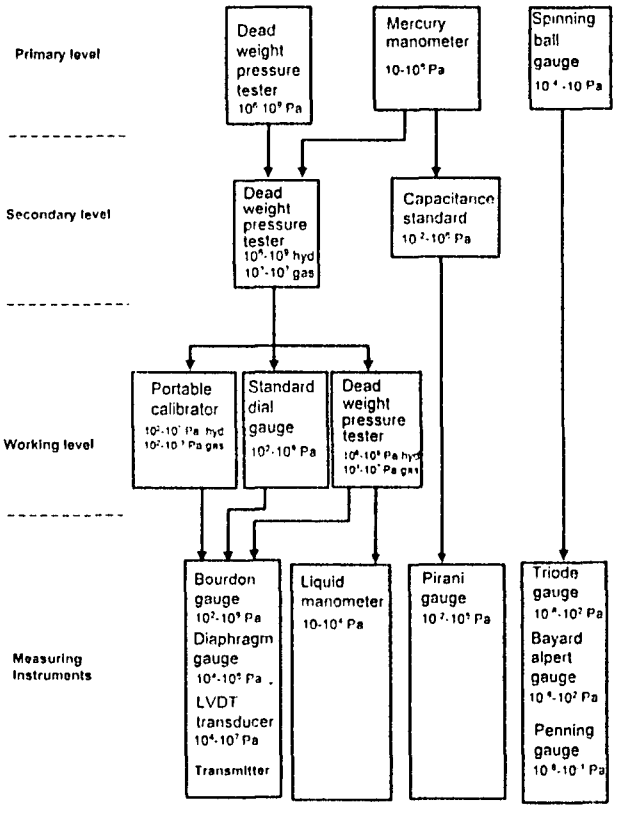


Figure 12.1 Hierarchy of pressure measurement standards

Primary standards are the dead weight pressure tester, mercury manometer and spinning ball gauge. Secondary standards are those calibrated against the primary standard, namely dead weight pressure testers and capacitance standards. Working standards are dead weight testers, precision dial gauges (bourdon tube or diaphragm type) and portable field type standards. A variety of these standards of different types (dead weight pressure balances, piezo resistive devices, strain gauge type) are available. These are very useful for field calibrations.

12.1.2 Test uncertainty ratio

The uncertainty required for a particular standard or test instrument is an important criterion to consider before a calibration is performed. The uncertainty assigned to a primary,

secondary or working standard is usually quoted at 95 % confidence level or coverage factor k=2. However this is only one component of the uncertainty budget. All other components of the system should be estimated. The usual criterion is that the combined uncertainty of the pressure calibration system including the higher level standard used should be at least 3 to 4 times smaller than the required uncertainty of the device under calibration. In some circumstances, when the item to be calibrated has a very low uncertainty a test –uncertainty ratio of 1:1 may have to be used.

12.1.3 Reference conditions

Primary, secondary and working level pressure standards are always calibrated in a laboratory having stable ambient temperature and pressure. Most pressure measuring instruments are also calibrated in an environment with stable ambient temperature and pressure. In field conditions using portable equipment such stable environments may not be found. In such cases it is difficult to evaluate the uncertainties of the calibration in a meaningful way as all effects of the poor environment may not be quantifiable. Also the reference standard itself may not have been calibrated under similar conditions. It is thus more common to calibrate measuring instruments also under stable conditions and apply separately determined corrections to take account of poor in service environments.

12.1.4 Local gravity

The generated pressure values given in a calibration certificate of a pressure balance are usually referenced to the standard value of the acceleration due to gravity, namely 9.80665 m/s^2. If the local value of gravity differs significantly from the standard gravity the generated pressure values need to be corrected using the value of local gravity.

12.1.5 Range of calibration

The range of calibration should be carefully considered. A pressure measuring instrument or standard is normally calibrated throughout is total range at least at five pressure levels. For determination of effective area of pressure balances at least ten pressure levels are required. To detect hysteresis effects, increasing as well as decreasing pressure is used. Calibration over 20 percent to 100 percent of rated range is usual.

12.1.6 Re-calibration interval

The interval between calibrations of a pressure standard or test instrument is dependant on the type of transducer, uncertainty specification, conditions and frequency of use. For instruments with electrically operated sensors and electronic signal conditioning circuits the manufacturer's specification for the device, particularly the specification for the long-term stability is a good starting point for the determination of the re-calibration interval. In most standards laboratories secondary standard dead weight testers (or pressure balances) are given a three-year re-calibration interval. Diaphragm capacitance standards and associated electronics are susceptible to drift and may need a shorter interval (one to two years).

It is possible to determine the approximate re-calibration interval after several calibrations, if *as found* calibration data are recorded in the calibration report. If the calibration values change significantly at each calibration, then the interval may be too long. On the other hand if there is no appreciable change in the calibration values, the interval may be too short.

12.1.7 Pipework and tubing

Most positive gauge pressure measuring instruments are calibrated by connecting their pressure ports to a pressure standard using suitable pipework or special tubing rated for high-pressure work. It is important to make sure that the pipework or tubing used is of good quality, undamaged and has a rating higher than the maximum pressure to be applied. The piping and joints should be inspected for leaks before the application of the maximum pressure. It is very important to ensure that the system is safe for operation at the maximum pressure envisaged . Guidance is available from a number of sources. Particularly the High Pressure Safety Code published by the High Pressure Technology Association.

12.1.8 Pressure medium

It is necessary to use the same pressure medium for the calibration as when the instrument is used. For example instruments for measuring gas pressure should not be calibrated using oil as the pressure medium. The reverse is also true. In circumstances where two different media have to be used a separator cell is used to transfer the pressure from one medium to the other.

The pressure medium used whether it be oil or a gas should be clean and free of moisture. Filtered air or dry Nitrogen is the preferred gas for calibration of gas pressure measuring instruments. Mineral or synthetic oils are used for hydraulic instruments. Certain oils may not be compatible with materials of some pressure system components. Also electrical conductivity of the oil is important when resistance gauges are being used. Instrument manufacturers usually recommend commercial oil types, which are suitable and their advice should be followed.

12.1.9 Instrument adjustment

Calibration of an instrument necessarily involves adjustment of the instrument where this is possible. Adjustments are performed until the deviations are minimum throughout the useful range. A number of repeat adjustments and test runs are required before an optimum level of deviations can be obtained.

12.2 Calibration techniques

12.2.1 Calibration of dead weight pressure balance

Generally working standard dead weight pressure testers are calibrated by comparing it with a secondary standard deadweight pressure tester in a procedure known as cross floating. Two methods are possible :

a) Method A-Generated pressure method

The deviation of the nominal pressure value (usually marked on the weights) from the generated pressure is determined at a number of loads. The repeatability of the pressure balance is also determined. The determination of the conventional mass values of the weights and other floating components is optional.

b) Method B-Effective area determination method

The following are determined :

i) the conventional mass values of all the weights, weight carrier and the piston of the pressure balance if removable.

ii) the effective area A_P of the piston-cylinder assembly of the pressure balance as a function of pressure, at the reference temperature (usually 20 °C).

iii) the repeatability as a function of the measured pressure.

In method A, the deviation of the nominal pressure from the generated pressure and its uncertainty at each pressure level is ascertained. Method B which is more time consuming, produces a complete calibration certificate with values for the effective area, mass values of the weights and their uncertainties

The choice of the procedure to be followed in a particular case depends on a number of considerations, the most important being the uncertainty of the instruments to be calibrated using the dead weight tester.

c) Cross-floating

In a cross floating system two pressure balances are interconnected into a common pressure system. When the loads on the two pressure balances are adjusted so that both are in equilibrium, the ratio of their total loads represents the ratio of the two effective areas at that pressure. The attainment of the equilibrium condition is the critical part of the measurement.

A single medium hydraulic cross float system between two dead weight pressure testers is shown in Figure 5.20. A variable volume pump is used to pressurize the system and to adjust the float positions of the two pressure balances. An isolation valves is used to isolate the pump from the system to check for leaks. The two pressure balances are isolated from each other for determining sink rates of each balance independently. A sensitive differential pressure indicator and a by pass valve are inserted in line between the two pressure testers. The differential pressure indicator though not essential serves a useful purpose by indicating the pressure difference between the two testers and speeds up obtaining a balance.

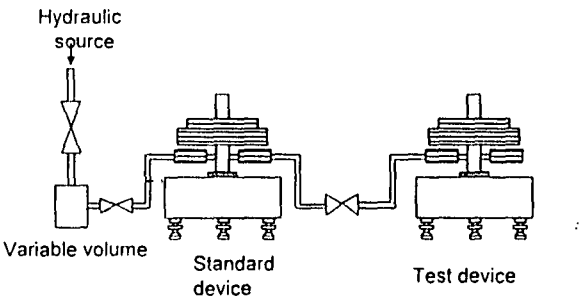


Figure 12.2 Typical arrangement for cross floating two hydraulic dead weight pressure testers

A similar arrangement is used in a two media (hydraulic and gas) cross float system except that an additional component, a media separator cell is required to transmit the pressure from one medium to the other. A differential pressure indicator is also used as in the case of the single medium system.

d) Estimation of uncertainty

The combined uncertainty of the measured pressure depends on a number of input uncertainties (See Chapter 9, -Uncertainty of measurements). The combined standard uncertainty, and the expanded uncertainty are calculated in conformity with the procedure given in Chapter 9, using the standard uncertainties estimated for each input component.

The main input components for method A and method B are listed below:

e) Method A

Type A uncertainties

Repeatability of the pressure balance is estimated at all loads by computing the standard deviation of the difference between the nominal and generated pressure. It is expressed in pascals, or as percentage of the nominal pressure.

Type B Uncertainties

a) Uncertainty of the pressure reference standard;

b) Uncertainty of the mass values,

c) Uncertainty of the local gravity,

d) Uncertainty due to temperature,

e) Uncertainty due to the head correction,

f) Uncertainty due to tilt (negligible if perpendicularity was duly checked),

g) Uncertainty due to air buoyancy, if significant,

h) Uncertainty due to spin rate and/or direction, eventually,

i) Uncertainty of the residual pressure (absolute mode only).

f) Method B

Type A uncertainty

Repeatability of the pressure balance is estimated at all loads by computing the standard deviation of the difference between the reference and generated pressure. It is expressed in pascals, or as percentage of the reference pressure.

Type B uncertainties

a) Uncertainty of the mass values,

b) Uncertainty of the measured effective area, including the uncertainty estimated using a type-A method,

c) Uncertainty due to the pressure distortion coefficient, when relevant, including the uncertainty estimated using a type-A method,

d) Uncertainty of the local gravity,

e) Uncertainty due to the temperature of the balance,

f) Uncertainty due to the air buoyancy,

g) Uncertainty due to the head correction,

h) Uncertainty due to tilt (negligible if perpendicularity was duly checked),

i) Uncertainty due to spin rate and/or direction, eventually,

j) Uncertainty of the residual pressure (absolute mode only).

12.2.2 Calibration of pressure gauge

a) Reference standard

A working standard dead weight pressure tester is used as the reference standard for calibration of pressure gauges of many types. Digital or dial type secondary standard pressure gauges are also used as a reference standard for calibration of less accurate test instruments.

a) Procedure

Bourdon tube and diaphragm type hydraulic gauges are cleaned with a solvent prior to connection to the pressure source. Pneumatic types do not require cleaning unless the exterior of the connecting tube are contaminated with dirt or dust.

The gauge is connected to the test gauge terminal of the pressure system as shown in Figure 12.x. Prior to commencement of calibration runs the gauge is exercised at least three times by applying pressure to the highest scale reading and reducing it slowly to the ambient pressure.

About ten test pressures covering scale range are applied at increasing and decreasing pressure cycles. The test instrument is adjusted if the pressures displayed by the test instrument are outside the tolerance band of the instrument,

Bourdon tube type instruments are adjusted by loosening the adjusting screw and lengthening or shortening of the connecting link (See Figure 12.4). Other types of adjustable instruments are adjusted according to the manufacturer's instructions. Usually adjustment is carried out after the calibration run. Two or more calibration runs may be required after adjusting the instrument to obtain minimum deviations throughout the entire scale.

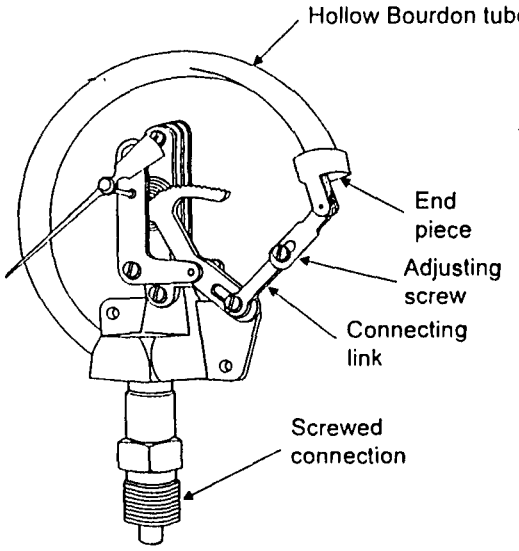


Figure 12.4 –**Bourdon tube pressure gauge**

12.2.3 Calibration of vacuum gauges

Vacuum gauges are calibrated by connecting them to a sufficiently large vacuum chamber. A general configuration used is shown in Figure 12.5.

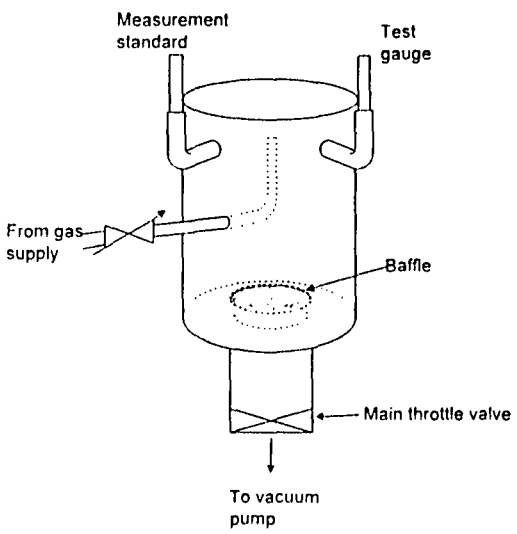


Figure 12.5 Configuration for Vacuum gauge calibration

The chamber is used only for calibration purposes and is kept as clean as possible. The vacuum is generated by an oil diffusion or turbo molecular pump backed by a rotary pump. A throttle valve is used to connect the vacuum pump to the chamber. High vacuum isolation valves are used to connect the test instrument and the measurement standard. A clean gas source (nitrogen) connected through a needle valve allows a small amount of gas to be admitted to obtain different pressure levels. It is possible to obtain an equilibrium constant pressure in the chamber by adjustment of the throttle valve and the needle valve. Pressure

indicated by the test instrument and the standard are recorded for each pressure level. Several repeat runs are carried out.

13 Calibration of force standards and test instruments

13.1 General considerations

The most important general concepts relating to calibration of force standards and measuring instruments are discussed in this section. The basic principles of calibration are similar for force standards as well as test instruments as both types rely on similar principles of operation as discussed in chapter 6. The significant differences are in respect of uncertainty, the specific reference standard to be used, reference conditions particularly ambient temperature and re-calibration interval,

13.1.1 Reference standard

The hierarchy of measurement standards used for calibration of force measuring instruments is given in Figure 13.1.

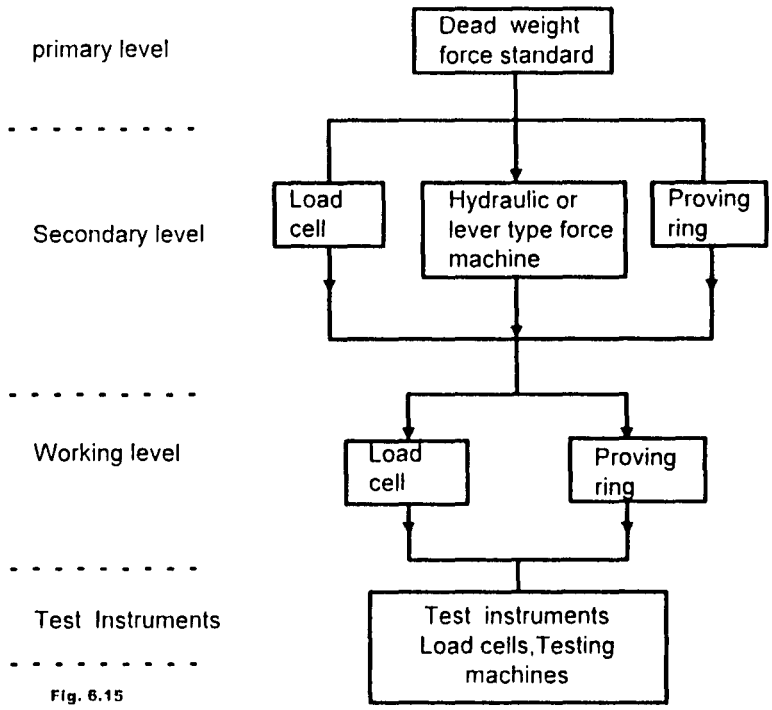


Figure 13.1 Hierarchy of force measurement standards

This diagram gives the next higher level standard that may be used for the calibration of a given standard or instrument. Primary standard is the dead weight force standard. Secondary standards are those calibrated against the primary standard, namely lever or hydraulic force standard machines, proving rings, load cells and other secondary standard force transducers. Proving rings and load cells are also used as force transfer standards. Working standards are proving rings and load cells used for the calibration of measuring instruments.

13.1.2 Test uncertainty ratio (TUR)

The test uncertainty ratio required for a particular standard or instrument is an important criterion to consider before a calibration is performed. The uncertainty assigned to a primary, secondary or working standard is usually quoted at 95 per cent confidence level or coverage factor k=2. The combined uncertainty of the force calibration system including the higher

level standard used should be at least 3 times smaller than the required uncertainty of the standard or instrument under calibration.

In the case of an instrument such as a load cell or an in built force measurement system, the required uncertainty is determined by the user, taking into consideration the requirements defined by the process (in process control) and regulatory standards (weights & measures, health & safety). Calibration uncertainty should be defined to meet these needs. Typical uncertainties of primary and secondary force standards are indicated in Table 13.1

Table 13.1- Typical uncertainties of force standards

Type of standard	Principle of operation	Relative uncertainty as percent of full scale*	Level of standard
Dead weight standard	Force is generated by suspending a known mass in the earth's gravitational field.	±0.002	Primary
Hydraulic amplification machine	A set of dead weights is used to generate pressure in a small piston cylinder assembly. This pressure is applied to a larger piston cylinder assembly amplifying the force.	±0.04	Secondary
Lever amplification machine	A set of levers is used to amplify the force generated by a small dead weight machine.	±0.04	Secondary
Proving ring	The deformation of an elastic metallic ring on application of force is detected using a dial micrometer or other device.	±0.01	Secondary
Load cell	The deformation of an elastic element on application of force is detected using electrical strain gauges or other device.	0.05	Secondary

*The uncertainty is at a confidence level of 95 %

(Reproduced from Guide to Measurement of Force with permission of the Institute of Measurement and Control. U.K)

13.1.3 Reference conditions

As all force transducers are temperature dependant, calibrations of force standards are done in a laboratory with controlled temperature and humidity conditions. The reference temperature of calibration of force measurement standards is either 23 °C or 25 °C.

Whenever possible, force measurement instruments should also be calibrated in a controlled temperature environment. Frequently this is not possible as the test instrument is located in a factory or a site where the ambient temperature is not controlled. In such cases the calibration could be done at the prevailing conditions. However the temperature of the sensing elements (both test item and standard) should be measured and temperature corrections applied.

13.1.4 Range of calibration

The range of calibration should be carefully considered. A force transducer is normally calibrated throughout is total range in tension or compression at least at 10 steps. To detect hysteresis effects, increasing force as well as decreasing force is used. Usually calibration over the range, 20 percent to 100 percent of rated output is more critical.

13.1.5 Scope of calibration

A force measurement system generally consists of a force transducer, indicating device, associated cabling and power supplies. Calibration of the entire system is the best solution. However this is not always practicable, in which event the transducer and instrumentation are calibrated separately to traceable standards.

13.1.6 Insitu or laboratory calibration

Secondary and working level force standards should always be calibrated in a laboratory having temperature and humidity control. In industrial situations, whether to calibrate a force measurement system in a laboratory or in-situ is dependant on a number of factors. In-situ calibration is very often necessitated by reasons of cost, to avoid disturbing the instrument or to calibrate exactly under conditions of use.

13.1.7 Re-calibration interval

The interval between calibrations of a force standard or instrument is dependant on the type of transducer, uncertainty specification and frequency of use. The manufacturer's specification for the device, particularly the specification for the long-term stability is a good starting point for the determination of the re-calibration interval. In most calibration laboratories secondary standard proving rings are given a three-year re-calibration interval. Resistance strain gauge load cells however require shorter intervals due to their inherent drift characteristics. Generally these are calibrated annually or even at shorter intervals. It is possible to determine the approximate re-calibration interval after several calibrations, if *as found* calibration data are recorded in the calibration report. If the calibration values change significantly at each calibration, then the interval may be too long. On the other hand if there is no appreciable change in the calibration values, the interval may be too short. Specific recommendations in respect of working standards are given in the next section.

13.2 Calibration of working standard force proving devices

13.2.1 Documentary standards

There are a number of international and national standards applicable to the calibration of working standard force proving devices (e.g proving rings and load cells) used for calibration of material testing machines and other force measurement systems. Two widely used standards are:

The international standard ISO 376 and

American Society for Testing & Materials standard, ASTM E 74.

13.2.2 Reference standard

Working standard devices (proving rings and load cells) are calibrated against a secondary standard proving ring, load cell or hydraulic or lever type force standard depending on their rated capacity. A test uncertainty ratio of at least 1:3 should be maintained.

13.2.3 Reference temperature

The calibration is conducted in an environment with ambient temperature of 18 °C to 28 °C stable to ± 1 °C. Most laboratories use the temperature of 23 °C ± 1 °C. Sufficient time is

allowed for the device under calibration to achieve temperature equalisation with the ambient.

13.2.4 Preliminary tests

It is common practice to carryout a few preliminary tests before undertaking the calibration of a proving device. The most common tests are overload, the method of application of the forces and the effect of a variation in supply voltage on the output of the device.

13.2.5 Overload test

The instrument is subjected to an overload within the range of 8 percent to 12 percent of the maximum load four times in succession. The overloading is maintained for a duration of 1 minute to 1.5 minutes.

13.2.6 Application of forces

The ability of the attachment system of the force proving instrument to apply the forces axially when the instrument is used in a tensile force application is tested. Also when the instrument is used in the compression mode, it is ensured that the deflection of the force proving instrument is not significantly affected by the characteristics of the bearing pads, namely its hardness and curvature of the bearing surfaces .

13.2.7 Variable voltage test

A change of the supply voltage by ± 10 percent should not produce any significant effect on the output of the force proving device.

13.2.8 Number of test loads

At least 30 load applications are required for a calibration and of these at least 10 must be at different loads. That is the load is applied at 10 different test points, three times, over the full range of the device giving rise to a total of 30 applications. Usually the instrument under calibration is rotated symmetrically on its axis to positions uniformly distributed over a 360° circle at intervals of 120° or 180°.

13.2.9 Preload

The preloading is done to establish the hysteresis pattern and is particularly required if the device has been out of use for some time or if the mode of loading is changed say from compression to tension in the case of dual mode devices. The device is subjected to the maximum force three times before the calibration run is started. The preload is maintained for a period of 1 to 1.5 minutes.

13.2.10 Load increments

After preloading, the calibration loads are applied starting from zero load and increasing to the highest load. Whether to return to zero load after each calibration load is decided based on the stability of the zero load reading and the presence of noticeable creep under load. However to sample the device behavior adequately a return to zero load should be made after application of not more than five consecutive calibration loads. The loading sequence is repeated a number of times (usually two or three times). Before each repeat the position of the device in the calibration machine is changed. A compression device is rotated on its axis by one third or one half turn (180° or 120°), keeping the same load axis while in a tensile calibration coupling rods are rotated one third or one half turn taking care to shift and realign any flexible connectors.

13.2.11 Calibration equation

The deflection of a proving ring or the reading indicated by a load cell for each calibration load is calculated from the following equation:

$$d_L = R_L - (R_{01} + R_{02})/2 \qquad (13.1)$$

where d_L – zero corrected deflection or reading of the device for calibration load L

R_L - measured deflection or reading at load L

R_{01} – zero reading before application of load L

R_{02} – zero reading after application of load L

A polynomial second-degree equation as given below is generally fitted to the load and deflection values obtained from the calibration:

$$d_L = A + BL + CL^2 \qquad (13.2)$$

Other forms and methods of fitting, including higher degree polynomials particularly for high resolution devices are also used.

Uncertainty

The uncertainty (U) is calculated from the following equation :

$$U = 2.4 \times s \qquad (13.3)$$

s is the standard deviation of the residuals i.e differences between the measured deflections (d_L) and their corresponding values obtained from the calibration fit equation (d_{FL}). The residuals (r_L) are calculated from equation :

$$r_L = d_L - d_{FL} \qquad (13.4)$$

and the standard deviation of n residuals from the equation :

$$s = \sqrt{\frac{\sum_{L=1}^{n} r_L^2}{(n-m)}} \qquad (13.5)$$

In this equation m is the number of co-efficients in the fitted curve (equation 13.2).

According to ASTM E74 the factor 2.4 has been determined empirically from an analysis of a large number of force measuring device calibrations and contains approximately 99 percent of the residuals for least square fits.

An example of data analysis of the calibration of a working standard proving ring is given in Table 13.2.

Sum of squares of residuals = 10.46 Div^2

Average force per deflection = 0.36 N/Div.

Standard deviation = 2.93 Div.

Standard deviation in newtons = 1.05 N

Uncertainty as percent of capacity = 0.53 percent

Equation of fit : deflection(d_L) = 0.08+1.04 x L+ 0.04 x L^2 (13.6)

The lower loading limit for use as a class AA (see section on classes of instruments) device is 2000 x 1.05 = 2100 N = 2.1 kN.

Temperature corrections

All mechanical force measuring instruments require temperature corrections when used at a temperature other than the temperature of calibration. The correction is effected using the following equation:

$$d_{Lt} = d_{L0}[1+k(t-t_0)] \quad (13.7)$$

where d_{Lt} - deflection for load L corrected to temperature t

d_{L0} - deflection for load L at calibration temperature t_0 and

k- temperature co-efficient of the instrument

For instruments having force transducers made of steel with not more than 7 percent alloying elements, the value k = 0.000 27 / °C may be used. In the case of transducers made of material other than steel or having electrical outputs, the temperature co-efficient determined experimentally and/or supplied by the manufacturer should be used.

The force corresponding to the corrected deflection at the calibration temperature is obtained from the calibration equation. An example is given below:

Example:

Material of the transducer : steel with less than 7 percent alloying elements

Temperature of the force proving instrument : 25 °C

Temperature of calibration : 23 °C

Observed deflection at 25 °C : 751.4 divisions.Using equation (13.7) the deflection corrected to 23 °C (d_{Lo}) is obtained ,

Table 13.2 Calibration of a working standard proving ring - data analysis

Applied force	Deflection	Temperature	Temperature corrected deflection	Deflection from equation of fit	Residual	Square of residuals	Force per deflection
kN	div.	°C	div.	div.	div.	div^2.	N/div.
20	28.4	23.6	28.4	28.88	0.48	0.23	0.70
40	74.3	23 2	74.3	73.68	-0.62	0.38	0.54
60	135.2	23.7	135.2	134.48	-0.72	0.52	0.44
80	211.1	23.4	211.1	211.28	0.18	0.03	0.38
100	304.1	23.6	304.1	304.08	-0 02	0.00	0.33
120	414.1	23.2	414.1	412.88	-1.22	1.49	0.29
140	537.9	23.8	537.8	537.68	-0.22	0.05	0.26
160	680.1	23.6	680.0	678.48	-1.62	2.62	0.24
180	836.6	23.7	836.4	835.28	-1.32	1.74	0.22
200	1010.0	23.5	1009.9	1008.08	-1.92	3.69	0.20

$$d_{Lo} = \frac{751.4}{[1+(25-23)\times 0.00027]} = 751.0 \qquad (13.8)$$

Using the calibration equation (13.2) the corresponding force is obtained :

$751.0 = 0.08+1.04 \times L+ 0.04 \times L^2$

The solution of this quadratic equation gives the value of the force as 179.4 kN.

Classes of instruments

ASTM E 74 defines two classes of instruments, *Class AA* and *Class A*. *Class AA* is specified for devices used as secondary standards. The uncertainty of these instruments as determined above should not exceed 0.05 percent of load. The lower load limit of the instrument is 2000 times the uncertainty in force units. e.g. If an instrument has an uncertainty of 20 N as calculated from equation 6.5 , then its lower load limit for use as a *Class AA* device is 20 x 2000 = 24000 N .On this basis, the uncertainty of the device for loads greater than 24000 N would be less than 0.05 percent.

Class A devices should have uncertainties less than 0.25 percent. The lower load limit of these instruments is given by 400 times the uncertainty calculated from equation 6.5. Thus for the instrument having 20 N uncertainty the *Class A* lower load limit is 20 x 400 = 8000 N.

The international standard ISO 376 classifies the instruments into four classes, 00, 0.5,1 and 2 based on five criteria. This classification is given in Table 13.3.

Table 13.3 Classes of force proving instruments

Class	Relative error of the force proving instrument					Uncertainty of applied calibration force
	Percent					Percent
	of reproducibility	of repeatability	of interpolation	of zero	of reversibility	
00	0.05	0.025	± 0.025	± 0.012	0.07	± 0.01
0.5	0.10	0.05	± 0.05	± 0.025	0.15	± 0.02
1	0.20	0.10	± 0.10	± 0.050	0.30	± 0.05
2	0.40	0.20	± 0.20	± 0.10	0.50	± 0.10

(Reproduced from ISO 376-1987 with permission of the International Organisation for Standardization)

13.3 Calibration of limited load devices

Elastic rings or other devices with dial indicators for sensing deflection are classified as limited load devices as large localized non linearities are introduced by their indicator gearing. These devices are to be used only at the calibrated loads and interpolation of values or use of curve fitting techniques are not recommended.

13.3.1 Re-calibration interval

ASTM E 74 recommends an interval of two years for mechanical force measuring instruments such as proving rings, amsler boxes, rings or loops with dial indicators or optical scales. Electrical force measuring instruments such as strain gauged load cells, rings or loops with differential transformers, variable reluctance sensors and piezo electric load cells are to be recalibrated one year after their first calibration and thereafter at intervals not

exceeding two years provided the changes of deflection between the most recent calibration and those from the previous calibration do not exceed 0.1 percent of the full load deflection.

An instrument should be recalibrated after repairs or if it has been subjected to an overload higher than the test over load.

13.4 Verification of tensile and compressive testing machines

13.4.1 Documentary standards

A number of standards give procedures for verification of material testing machines and other force measurement systems. Two widely used standards are:

The international standard ISO 7500-1 and

American Society for Testing & Materials standard, ASTM E 4.

13.4.2 Reference standard

Load cells or proving rings are the commonest devices used for verification of tensile or compressive testing machines. In some instances if the maximum capacity of the testing machine is relatively low, it is possible to use weights of known value and uncertainty.

The force proving instrument should comply with the requirements of ISO 376 and should be equal to or better than the class for which the testing machine is to be calibrated. If dead weights are used then the relative uncertainty of the force generated by these weights should be less than 0.1 percent .

13.4.3 Temperature equalisation

A sufficient period of time is allowed for the force proving device to attain temperature equilibrium with the ambient. The temperature of the force proving device should remain stable to within ± 2 °C during each calibration run. It is good practice to attach a thermocouple or a liquid in glass thermometer to the force proving device to measure its temperature and effect a temperature correction.

13.4.4 Conditioning of the testing machine

The testing machine is conditioned by applying the maximum force three times with the force proving device placed in position.

a) Application of test forces

Generally three series of measurements with increasing forces are taken. At least five test forces between the 20 percent and 100 percent of each range are required. If it is necessary to verify below 20 percent of the range, then test forces at 10,5,2,1,0.5,0.2 and 0.1 percent of the scale down to and including the lower limit of the calibration are applied. The lower limit of the calibration is determined as follows:

Class	lower limit
00	400 x resolution
0.5	200 x resolution
1	100 x resolution
2	67 x resolution

An elastic force proving device can be used in two different ways. The load is increased until the testing machine readout reaches a nominal graduation. The reading of the elastic proving device is recorded. Alternatively the force may be increased until a preset value of the elastic proving device is reached and the readout of the testing machine is recorded.

The indicator reading is set to zero for both the test machine and the force proving device before each series of measurements. The zero readings are taken again 30 s after the removal of the force.

13.4.5 Data analysis

The arithmetic mean of the values obtained for each series of measurements is calculated. The relative accuracy and relative repeatability of the force measuring machine is calculated from these data.

a) Parameters of assessment

Table 13.4 Parameters for assessment of testing machines

Parameter	Definition
Relative accuracy	$q = \frac{F_i - \bar{F}}{\bar{F}} \times 100$
Relative repeatability	$b = \frac{F_{max} - F_{min}}{\bar{F}} \times 100$
Relative reversibility	$v = \frac{F_i' - \bar{F}}{\bar{F}} \times 100$
Relative resolution	$a = \frac{r}{F} \times 100$
Relative zero error	$f_{io} = \frac{F_{io}}{F_N} \times 100$

Where,

F- Force value indicated by the force proving device with increasing test force ;

$\bar{F}$ - Arithmetic mean of several values of F.

F_i - Force indicated by the force indicator of the testing machine with increasing test force ;

F_i' -Force indicated by the indicator of the testing machine with decreasing test force ;

F_{max} - Highest value of F_i for the same discrete force;

F_{min} - Lowest value of F_i for the same discrete force;

F_{io} - Residual indication of the indicator of the testing machine;

F_N - Maximum capacity of the measuring range of the testing machine.

r -Resolution of the force indicator of the testing machine.

a) Classes of testing machine range

ISO 7500-1 classifies force testing machines into four classes as given in Table 13.5 :

Table 13.5 Classes of testing machines

Table 13.5 Classes of testing machines
(Reproduced from ISO 7500-1:1999 with permission of the International Organisation for Standardization)

initial zero	0	0	0
Final zero	0.2	0.1	0.2
Relative zero error, %	0.2	0.1	0.2

Table 13.6 – Calibration data analysis of material testing machine

Test machine indication	**Proving device reading**			**Mean reading of proving device**	**Relative accuracy**	**Relative repeatabiliy**
kN	kN			kN	Percent	Percent
	Run 1	**Run 2**	**Run 3**			
20	20.4	20.3	20.3	20.3	21.5	0.5
40	40.8	40.9	40.6	40.8	2	0.7
60	61.1	61.2	61.3	61.2	2	0.3
80	81.2	81.3	81.6	81.37	1.7	0.5
100	101.4	101.2	101.7	101.43	1.4	0.5

Table 13.7 – Relative Zero Error

Class of machine range	**Maximum permissible value, Percent** Relative error of				**Relative resolution**
	Accuracy q	**Repeatability** b	**Reversibility** v	**Zero** f_0	a
0.5	±0.5	0.5	± 0.75	± 0.05	0.25
1	±1.0	1.0	± 1.5	± 0.1	0.5
2	±2.0	2.0	± 3.0	± 0.2	1.0
3	±3.0	3.0	± 4.5	± 0.3	1.5

Example 2 :

The verification data of a tensile testing machine of capacity 100 kN is given in Table 13.6:

Using the definition given in Table 13.4 , the relative resolution of this range is calculated as follows :

$$\text{Relative resolution} = \frac{0.1}{100} \times 100 = 0.1$$

In the range 20 kN – 100 kN the testing machine has the following characteristics :

Relative accuracy - 2 per cent

Relative repeatability – 0.7 per cent

Relative zero – 0.2 per cent

Relative resolution – 0.1 per cent

The relative reversibility was found to be 1.2 per cent though not recorded in Table 13.7. From these data the 20 kN –100 kN range of the machine can be classified as belonging to Class 2.

13.4.6 Re-verification interval

The re-verification interval of a force testing machine depends on the type of machine, the level of maintenance and the amount of use. A machine should preferably be verified at intervals not exceeding 12 months. A machine which has been re-located or has been subjected to major repairs should be re-verified.

14 Calibration of thermometers and thermometry equipment

14.1 Introduction

General guidance on calibration of mercury in glass thermometers, platinum resistance thermometers, thermocouples and other thermometry equipment such as solid block calibrator, temperature indicator/simulator are given in this chapter.

14.2 Essential features of calibration

The calibration of thermometers of all types is carried out by two main methods, fixed point calibration and comparison calibration.

14.2.1 Fixed point calibration

Fixed point calibration is performed by using ITS-90 fixed points in a fixed point bath or furnace. Carefully performed fixed point calibrations yield very small uncertainties and are usually required only for those thermometers, which are used as secondary standards. For most instruments used in industry fixed point calibration is not required.

14.2.2 Comparison calibration

Comparison calibration is performed in a calibration bath in comparison with a secondary or working standard thermometer. Almost all industrial temperature measuring instruments are calibrated by this method.

14.2.3 Calibration hierarchy

The hierarchy of calibration standards used for calibration of temperature measuring instruments is given in Figure 14.1.

This diagram gives the next higher level standard that should be used for calibration of a given standard or instrument. Primary standards are those designated by the ITS 90 definition. Secondary standards are those calibrated against the primary standards, namely standard platinum resistance thermometers (SPRT) upto 1000 °C , Type R or S thermocouples upto 1600 °C and optical pyrometers upto 3000 °C.

Working standards are generally platinum resistance thermometers (upto 1000 °C), thermocouples upto 1300 °C and reference standard mercury in glass thermometers (upto 500 °C) . However mercury in glass thermometers are rarely used as working standards nowadays due to the availability of low cost very stable platinum resistance thermometers.

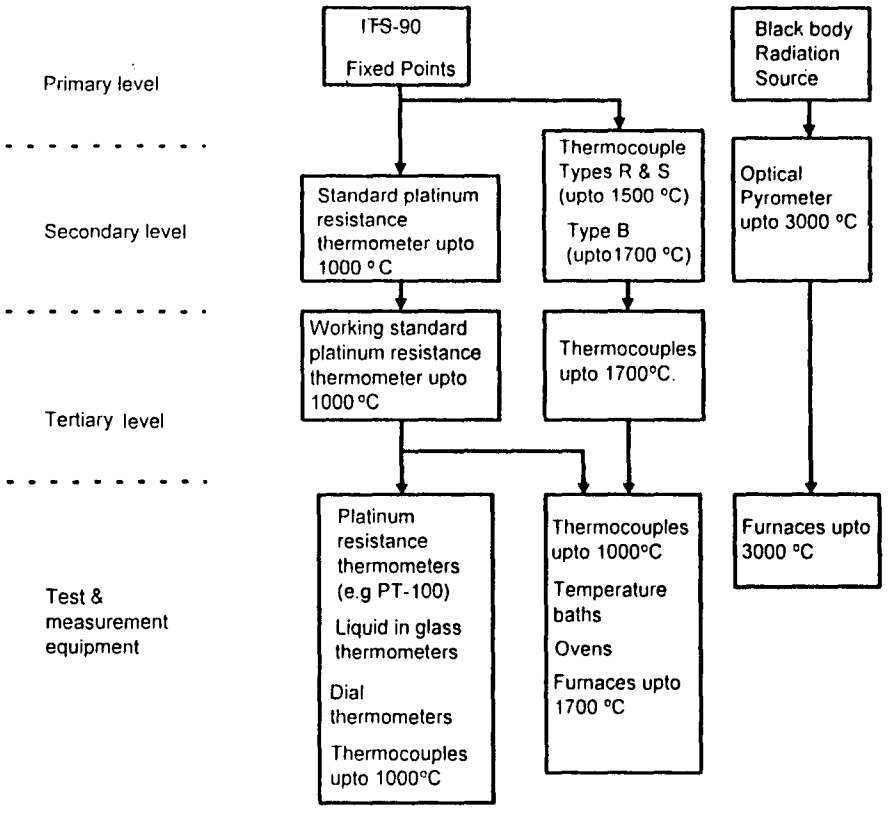


Figure 14.1 Hierarchy of temperature measurement standards

In the high temperature area (1600 °C to 3000 °C) the optical pyrometer is used as the secondary standard.

14.2.4 Test uncertainty ratio

The choice of the reference standard and the procedure for calibration is mostly dependant upon the uncertainty of the item under calibration. Generally it is the practice of accredited metrology laboratories to achieve a test uncertainty ratio of at least 1:4. i.e. the uncertainty of the reference standard is at least ¼ that of the item under calibration. However in some cases this may not be achieved. In thermometry, absolute uncertainty of the calibrated item is more significant and is generally specified.

14.3 Calibration equipment

14.3.1 Ice point bath

An ice point bath is a convenient method of checking the zero of a thermometer. The ice point is the equilibrium temperature between ice and air saturated water. An ice point bath can be easily constructed using a wide mouthed dewar flask, a siphon tube, ice and distilled water. A flask of diameter 80 mm and depth of about 400 mm would be adequate for most purposes, Figure 14.2

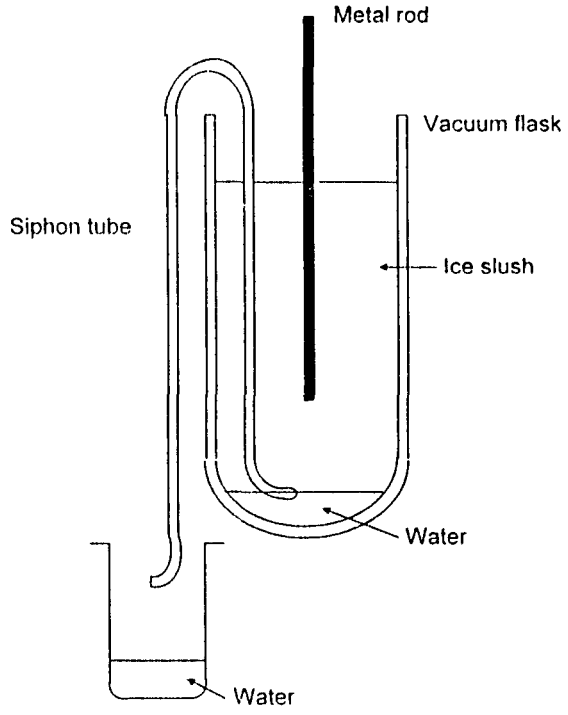


Figure 14.2 Ice point bath

The ice is made from distilled or de-ionized water and finely crushed to small chips measuring 2 mm- 5mm.The flask is about one third filled with distilled water and the crushed ice is added. The mixture is compressed to form a tightly packed slush, drained and remixed until there is no free water left, but the ice is completely wet. The ice will look glassy when it is completely wet. A siphon is placed in the flask to remove excess water formed as the ice melts.

The bath mixture is allowed about 30 minutes to attain temperature uniformity throughout before it is used. Ice should be added and excess water removed while the bath is being used. If precautions are taken to prevent contamination of ice and water, the ice point can be realised to better than $\pm 0.01\ ^{\circ}C$

Commercial versions of ice point baths with an integral electrically operated stirrer are also available.

14.3.2 Stirred oil bath

Stirred oil baths are suitable for comparison calibrations in the range $-30\ ^{\circ}C$ to $+\ 300\ ^{\circ}C$. Beyond this temperature range baths using other media are used.

There are two main types of stirred oil baths, concentric tube type and parallel tube type. The schematic of a concentric tube type bath is shown Figure 14.3. The bath consists of two concentric cylindrical chambers. Fluid is filled in both chambers and is made to flow through the inner and outer chambers using a pump, which is fitted, at the bottom of the inner chamber. A bank of heaters is used to maintain the temperature of the bath fluid at a set level or some baths incorporate a control system to raise the temperature slowly at a desired rate.

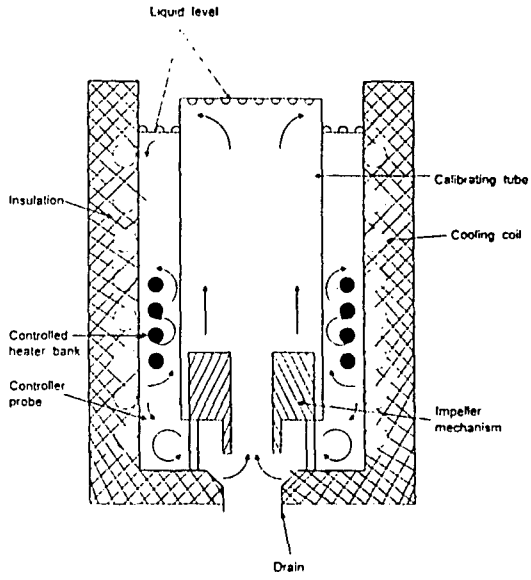


Figure 14.3 Schematic of concentric tube type bath

Two main criteria in choosing a bath are its *stability* and *uniformity*. Stability is the maximum variation of temperature of the fluid at the maximum operating temperature after stabilisation of the bath. Uniformity is defined as the maximum difference in temperature at two different points in the bath at the same instant of time. The very best baths commercially available can achieve ±0.001 °C for both stability and uniformity.

Different fluids are used depending on the temperature range required. Usually mineral or silicone oils are used in the range 20 °C to 250 °C. In the negative temperature range a number of other fluids including ethylene glycol (upto –30 °C) are used. The boiling point as well as the flash point of the oil should be taken into consideration in choosing the higher operating temperature. Also the viscosity of the oil comes into play at the lower end of the range as some oils will get very thick and will not flow readily at low temperatures.

14.3.3 Fluidised alumina bath

The basic construction of a fluidised alumina bath is shown in Figure 14.4.

The bath consists of a container of aluminium oxide powder sitting on a porous base plate. Pressurised air is passed through the base plate to impart kinetic energy to the powder so that it behaves similar to a fluid. When the powder is fluidised it displays good flow and heat transfer characteristics.

However the fluidised medium itself can not achieve very good temperature stability and uniformity. Metal blocks are used to improve on these parameters. Fluidised baths operable in the range 50 °C to 700 °C with stability not exceeding ± 0.005 °C are available commercially.

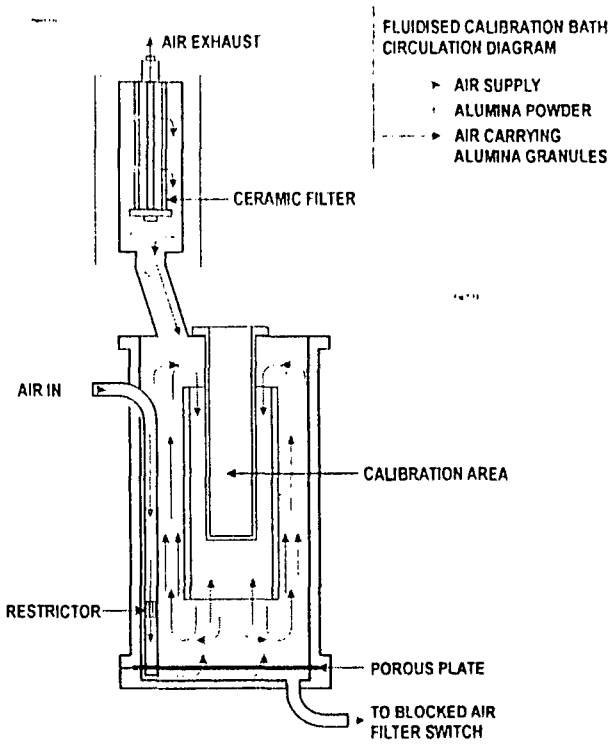


Figure 14.4 Schematic of a fluidised alumina bath (Source: Isothermal Technology Ltd.,U.K)

14.3.4 Tube furnace

Tube furnaces are generally used for calibrating thermocouples to high temperatures (1800°C).A simplified diagram of a three zone tube furnace is shown in Figure 14.5.

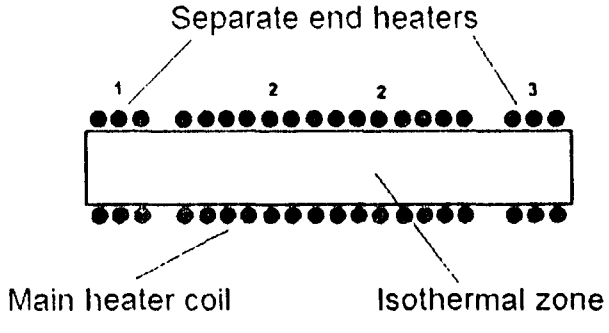


Figure 14.5 -Schematic of three-zone tube furnace

Tube furnaces can give good results, but can have non-uniform temperature gradients along their length due to cold-ends. The longer the furnace, the less effect the cold-ends will have. The cold-end effect is minimised by putting separate heaters at the ends of the tube to counteract the cold-end effect. The extra heaters are controlled separately from the main heater

Metal inserts can also be used to reduce temperature gradients but the metal can out-gas and contaminate the thermometers placed in it.

14.3.5 Dry block calibrators

Dry block calibration systems are very convenient portable temperature calibrators. A number of different designs are available. Two common systems are illustrated in Figure 14.6.

Design A is considered a poor design as the temperature of the block is measured at a point far away from the probe under calibration. In design B, a separate hole is provided for insertion of a standard thermometer probe.

Baths having a range of –30 °C to 1100 °C are commercially available. Most manufacturers claim stabilities of the order of ± 0.01 °C upto 700 °C.

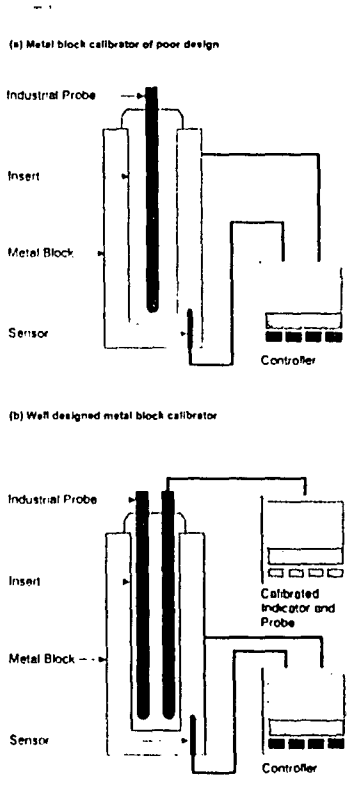


Figure 14.6 Schematics of dry block calibration baths

14.3.6 Simulators

Thermocouple simulators generate a voltage corresponding to an input temperature level, whereas resistance simulators provide a resistance output corresponding to an input temperature. Simulators can be used conveniently to verify the reading of display units of thermocouple and resistance thermometers, particularly when they are used in conjunction with a temperature transmitter. It is vital to remember that the simulator does not calibrate or verify the output of the sensor, calibration of which is vital to attain the required accuracy.

Generally thermocouple simulators are based on the electromotive force (emf) values given in reference tables for the letter designated thermocouple types. Resistance simulators are based on the resistance variation of the Pt-100 RTDs specified in the international standard, IEC 60751.

14.4 Calibration of liquid in glass thermometers

14.4.1 Recalibration interval

The period of validity of calibration of a liquid in glass thermometer is dependant on number of factors, namely,

The secular change-this is dependant on the age of the thermometer and the degree of annealing,

The uncertainty permissible on the reading,

The pattern of usage of the thermometer, particularly rough handling or wide temperature cycling

A regular ice point test, at least once in six months would reveal any changes of calibration occurring due to the secular change of the thermometric glass. If a significant change has occurred it is best to recalibrate the thermometer over the entire working range. If the thermometer has been subjected to rough handling or wide temperature fluctuations the calibration may change and in these cases a recalibration is called for.

After a few calibrations it is possible to determine an optimum recalibration interval by examining the calibration data. If the correction terms are essentially the same, it could be assumed that the thermometer is stable and the recalibration period can be extended. If on the other hand a more or less constant change at all test points are shown, the thermometer is still not stable and frequent ice point checks and yearly recalibration would be required.

14.4.2 Secular change

In a glass thermometer the bulb is continuously recovering from strains introduced during manufacture, when the glass was heated to 500 °C–600 °C. This recovery manifests itself as a contraction of the bulb and is known as secular change. In a new thermometer the contraction is relatively rapid and the rate decreases with time. The contraction of the bulb affects the readings significantly as the bulb volume is large in comparison to the stem volume. An ice point check is a useful method of tracking the changes in reading due to this effect. Figure 14.7 shows the effect of secular change on new and well annealed thermometers. In a well annealed thermometer, the drift due to secular change is normally less than one scale division per five years.

14.4.3 Temporary depression of zero

Glass is basically a liquid but in solid form at ambient temperature (super cooled liquid). Its molecules are relatively free to move, even at ambient temperature. Heating of glass expands it but subsequent cooling does not contract it back to its original volume. The effect occurs every time a thermometer is heated and is called the 'temporary depression of zero'. The temporary depression is normally about 0.1 percent of the reading or smaller, and lasts for a few days with residual effects detectable for months.

14.4.4 Reference standard

Although in the past working standard liquid in glass thermometers were used as reference standard, nowadays it is more common to use a working standard platinum resistance thermometer (WPRT), as WPRTs covering the entire working range of liquid in glass thermometers are available.

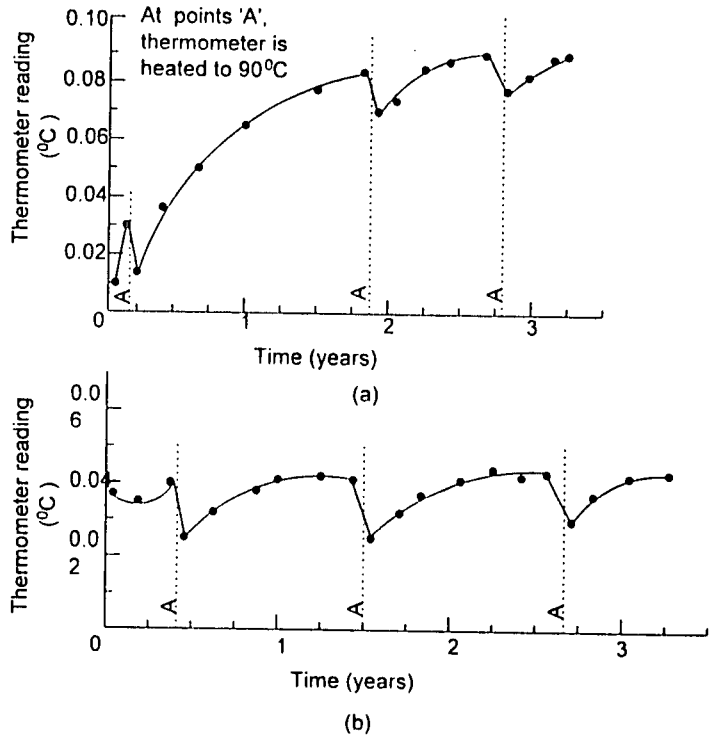


Figure 14.7 Effect of secular change on (a) new and (b) well-annealed thermometers (Source: CSIRO, Australia)

14.4.5 Number of test temperatures

The test temperatures at which calibrations are to be carried out is dependent on the type and range of the thermometer. Generally about five test temperatures over the working range is adequate. The exact temperatures of calibration are specified for thermometers conforming to a particular specification,. For example, the calibration temperatures for ASTM thermometers are given in ASTM E1 specification.

14.4.6 Procedures

a) Examination and assessment

A thermometer submitted for calibration should be examined carefully for construction and handling faults. The most common handling faults are :

a) Broken liquid column,

b) Gas bubbles,

c) Drops of liquid in expansion chamber or bore and

d) Worn pigment in scale markings.

Most of the other faults are due to manufacture:

a) Uneven or missing divisions,

b) Oxidation of mercury,

c) Thick scale lines

d) Excessive strain in the glass,

e) Distorted capillary,

f) Foreign matter in the bore.

The faults that can be rectified are fixed before calibration, and thermometers that can not be repaired should be rejected.

b) Repair of faults

Separated column

The bulb is immersed in a bath of crushed ice so that all the liquid (usually mercury) is drawn into the bulb. The separated sections can then be rejoined by gentle tapping.

Gas bubbles

The bubble is moved to the top of the bulb, preferably right under the capillary, by keeping the thermometer upright and tapping gently. Once the bubble is trapped between the liquid in the bulb and the capillary, the process used for rejoining a separated column is used.

Mercury droplets in capillary

If the droplets are totally separated from the liquid column, heating the thermometer until the liquid column reaches them can pick them up.

Faint scale markings

Etched markings are re-pigmented using a proprietary pigmenting solution or by rubbing with a mixture of sodium silicate, water and black oxide (MnO_2). Care should be taken however, not to let the excess mixture dry on the thermometer.

Etching

If there is no serial number or if other required markings are absent on a thermometer, it is necessary to engrave or etch markings on it. Marking tools with tungsten carbide tips can be used for engraving markings, though this has to be done with care.

An alternative method that has been utilized in most laboratories in the past is etching using hydrofluoric acid. Hydrofluoric acid is extremely dangerous and should not be allowed to touch the skin. Also hydrofluoric acid etching should not be attempted unless the laboratory has safety procedures and facilities for handling dangerous chemicals. The method of hydrofluoric acid etching is given below :

The following procedure should be carried out inside a fume cupboard. The operator should wear rubber gloves and appropriate eye protection equipment. The thermometer is first degreased with a solvent such as white spirit. The top 50 mm are then dipped in a bath of melted wax (microcrystalline) maintained at such a temperature that a thin layer of wax is left on the dipped portion of the stem. When the wax is set the required marking is made by cutting through the wax layer using a stylus. The wax chips produced are brushed off with a soft brush. The hydrofluoric acid is then painted on the wax covered stem and left for 4 minutes. The acid is removed by washing with water and the wax is removed by remelting and wiping off. The etched markings are filled with black filler while the thermometer is still warm.

c) Conditioning

There are number of conditioning routines described in the literature. Thermometers to be used over 300 °C or those which have not been annealed need conditioning prior to calibration. The thermometer is thermally cycled to the highest temperature marking (or highest temperature of use) and the stability of the ice point is checked after storage at room temperature for three days.

d) Calibration equipment

In the temperature range –80 °C to about 250 °C, a stirred liquid bath is used as the heat transfer medium. Above 250 °C a salt bath or a fluidised alumina bath is used. When using a stirred liquid bath the fluid appropriate to the temperature range and bath flow characteristics should be used. Some recommendations are given in Table 14.1:

Table 14.1 – Fluids for stirred liquid baths

Temperature range, °C	Fluid
-80 °C to + 30 °C	Methanol or Halocarbon 0.8 oil
-20 °C to 100 °C	Ethanol
+ 5 °C to +95 °C	Distilled water
+80 °C to +250 °C	Silicone oil (specific grade complying with bath manufacturer's recommendation should be used)

e) Partial immersion thermometers and stem corrections

A thermometer should be used vertically and in the condition of immersion given in the calibration certificate (or engraved on the stem). When an immersion depth, different to that of calibration has to be used for some reason, a correction is required to take account of the temperature of the emergent liquid column. This is known as the stem correction. The stem correction is worked out using the formula,

$$\delta t = k\, n\, (t_1 - t_2) \qquad (14.1)$$

Where k is the apparent thermal expansion coefficient of the liquid in the type of glass from which the stem is made, t_1 and t_2 are the average temperatures of the emergent columns during calibration and use, respectively and n is the number of degrees equivalent to the length of the emergent liquid column.

For most mercury in glass thermometers k = 0.00016 /°C and for spirit in glass thermometers, k = 0.001 /°C.

The temperature of the emergent column is measured either by the use of a special thermometer with bulb length slightly longer than the emergent column (Faden thermometer) or a short stem thermometer. Some calibration laboratories use thermocouples to measure stem temperatures during calibration. The method of using a Faden thermometer to measure the emergent stem temperature is shown in Figure 14.7.

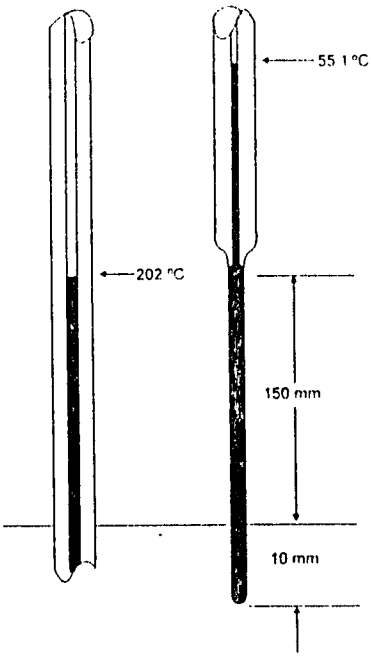


Figure 14.8 Use of a Faden thermometer to measure emergent stem temperature of a partially immersed thermometer

In the example shown in Figure 14.8, the length of the emergent column of the main thermometer is 150 mm and a Faden thermometer of bulb length 160 mm is placed alongside the main thermometer with 10 mm of its bulb in the comparison bath. This ensures that the Faden thermometer bulb simulates the condition of the emergent stem. The average temperature of the emergent liquid column (t_1 or t_2 of equation 14.2) is calculated as follows:

$$\frac{55.1\times 160 - 202\times 10}{150} = 45.3\ ^\circ C \qquad (14.2)$$

f) uncertainty

An analysis of the uncertainty of the test temperature reading is shown in the Ishikawa diagram of Figure 14.9

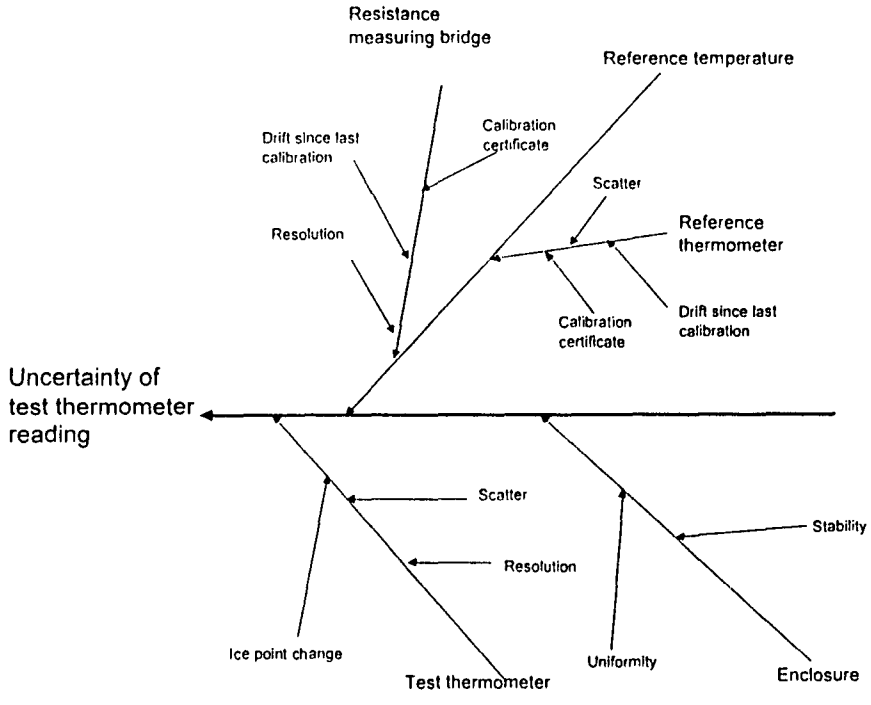


Figure 14.9 Ishikawa diagram showing contributory factors of test thermometer uncertainty

Reference temperature-The uncertainty of the reference temperature consists of the following uncertainties :

a) Calibration uncertainty of the reference thermometer.

b) Drift since its last calibration,

c) Scatter,

d) Uncertainty of the resistance measuring bridge, consisting of its calibration uncertainty, scatter, drift from the last calibration and resolution of its display,

Enclosure- Temperature uniformity and stability of the calibration bath contributes an uncertainty component to the measured value. This is known as transfer uncertainty and is determined for each bath and included.

Test thermometer- Scatter, resolution and ice point change are the main uncertainty components arising from the test thermometer.

e) The scatter is estimated from the standard deviation of three or more readings taken at a given test temperature.

f) Since it is possible to read a thermometer to about 1/10 of a graduation, the uncertainty due to resolution is estimated by taking 1/20 of a graduation as the half interval of a rectangular distribution.

g) The ice point is measured before and after a calibration and the change in the ice point value is taken as the full interval of a rectangular distribution.

14.5 Calibration of Standard Platinum Resistance Thermometers (SPRT)

14.5.1 Reference standard

The calibration of standard platinum resistance thermometer is done using fixed points. A working standard platinum resistance thermometer (WPRT) may be done by comparison with a standard platinum resistance thermometer.

14.5.2 Conditioning

SPRTs require periodic annealing to relieve accumulated strain in the wire. It is normal practice to anneal most SPRTs at about 450 °C for a sufficient time to stabilise the triple point resistance (R_{tp}). An SPRT whose R_{tp} increases during annealing is considered to be an unsatisfactory instrument and is rejected.

Conditioning a thermometer for use above 500 °C introduces a number of problems and a different conditioning procedure is used for such thermometers. A thermometer annealed at a temperature higher than 450 °C is immediately placed in a furnace operating at about the same temperature and the furnace temperature is ramped down at about 1 °C /min until below 400 °C. This procedure is carried out during initial annealing, during calibration and whenever the thermometer is used above 450 °C.

14.5.3 Insulation resistance

The insulation resistance of a metal sheathed thermometer is measured to confirm that there is no build up of moisture in the insulation.

14.5.4 Triple point resistance

In the case of a SPRT, the resistance at the triple point of water is measured. Generally the R_{tp} value should not differ by more than 200 micro ohms (for nominal 100 ohm PRTs) from its value measured at the previous calibration. If this limit has been exceeded the thermometer requires conditioning and re-calibration.

14.5.5 Calibration

An SPRT is calibrated using a number of fixed points. Sensors of ITS-90 interpolation instruments are made from high purity platinum. An acceptable platinum resistance thermometer must satisfy at least one of the following two relations:

$W(T_{ga}) \geq 1.11807$ or $W(T_{Hg}) \leq 0.844\,235$

where $W(T_{ga})$ and $W(T_{Hg})$ are resistance ratios at the gallium point and the mercury point .In addition an acceptable PRT that is to be used up to the freezing point of silver must also satisfy the relation :

$W(T_{ag}) \geq 4.2844$

In the above equations $W(T_{90})$ is the resistance ratio defined as :

$$W(T_{90}) = \frac{R(T_{90})}{R(273.16)}$$

In the range 0 °C to 961.68 °C, the fixed points of water (triple point), tin, zinc, aluminium and silver are used for the calibration. In the sub range of –39 °C to + 232 °C three additional fixed points, namely freezing point of indium, melting point of gallium and triple point of mercury are used.

14.5.6 Reference equations

The ITS-90 definition provides the reference functions to obtain ITS-90 temperatures from resistance measurements of an interpolating SPRT. In each of the resistance thermometer ranges, T_{90} is obtained from $W_r(T_{90})$ as given by the appropriate reference function (Equations 14.3 or 14.4) and the deviation $W(T_{90})-W_r(T_{90})$. At defining fixed points this deviation is obtained directly from the calibration of the thermometer; at intermediate temperatures it is obtained by means of the appropriate deviation functions (equation 14. 5).

For the range 0 °C to 961.68 °C the following reference function is defined:

$$W_r(T_{90}) = C_O + \sum_{i=1}^{9} C_i \left[(T_{90}/K - 754.15)/481)^i\right] \tag{14.3}$$

Also an inverse function to within 0.13 mK is :

$$T_{90}/K - 273.15 = D_O + \sum_{i=1}^{9} D_i \left[(W_r(T_{90}) - 2.64)/1.64\right]^i \tag{14.4}$$

The values of the constants C_o,D_o Ci and Di are given in the ITS-90 definition and are reproduced in Appendix 1.

For the same range the deviation function is :

$$W(T_{90}) - W_r(T_{90}) = a\left[W(T_{90}) - 1\right] + b\left[W(T_{90}) - 1\right]^2 + c\left[W(T_{90}) - 1\right]^3 + d\left[W(T_{90}) - W(660.323\ ^\circ C)\right]^2 \tag{14.5}$$

For a given thermometer a, b, c and d, are determined by calibrating the thermometer (i.e determining $W(T_{90})-W_r(T_{90})$) at the triple point of water (0.01 °C) ,and at the freezing points of tin (231.928 °C), zinc(419.527 °C),aluminium (660.323 °C) and silver (961.78 °C).Between the freezing point of aluminium and that of silver the value of d=0.

Similar reference and deviation functions are given in the ITS-90 defintion for all other ranges of temperature.

14.6 Calibration of Industrial Platinum Resistance thermometers

14.6.1 Ice point resistance

In the case of industrial PRTs an ice point resistance measurement is made. The resistance should be within 0.2 % of the nominal resistance. New thermometers should have the ice point resistance within 0.1 % of the nominal value.

Higher resistance values indicate contamination or exposure to vibration and shock. Low resistance values are indicative of moisture build up in the insulation or short circuited lead wires. The resistance is measured before and after the calibration to assess the stability of the thermometer.

14.6.2 Calibration

An industrial resistance thermometer can be calibrated in comparison with a working standard platinum resistance thermometer (WPRT). The comparison is carried out in a stabilised bath (up to about 700 °C). Comparison at five or six test temperatures is sufficient to obtain a calibration.

The recent introduction of slim metal clad fixed point cells which can be used in combination with small, light weight (bench top or cart mounted) furnaces has also facilitated the calibration of industrial grade PRTs. These fixed point cells are available for mercury, gallium, indium, tin, zinc, and aluminum points with uncertainties ranging from ± 0.001 °C to ± 0.005 °C.

14.6.3 Equations of fit

IEC 60751 defines the temperature –resistance relationship for industrial grade PRTs in the temperature range 0 to 850 °C by a simple quadratic equation :

$$R_t = R_0\left[1+At+Bt^2\right] \qquad (14.6)$$

In the range –200 °C to 0 °C a further term is used.

$$R_t = R_0\left[1 + At + Bt^2 + C(t-100)t^3\right] \qquad (14.7)$$

In the above equations R_t and R_0 are the resistance of the thermometer at the ice point and the temperature t.

The calibration of the thermometer thus consists of determining the A, B and C in the respective temperature ranges. Though only three test temperatures are required to determine these constants, generally about ten test points are used so that a least squares fit can be obtained.

14.7 Resistance measurement

a) DC methods

The simplest method of measuring the resistance of a PRT is to use a DC bridge. For two terminal thermometers a simple Wheatstone bridge is used. A modified Wheatstone bridge or a Mueller bridge can be used for three terminal and four terminal thermometers. Several configurations of DC bridges are shown in Figure 14.10. The use of a potentiometer is another method for measuring resistance.

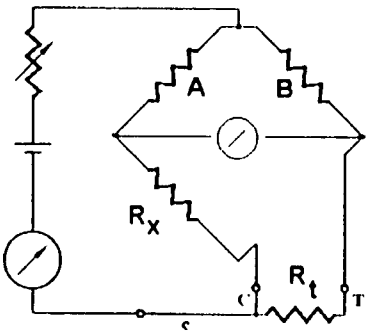
Three main sources of error are present in DC systems; thermoelectric effects, electrolytic effects and amplifier offset voltages and currents.

b) AC methods

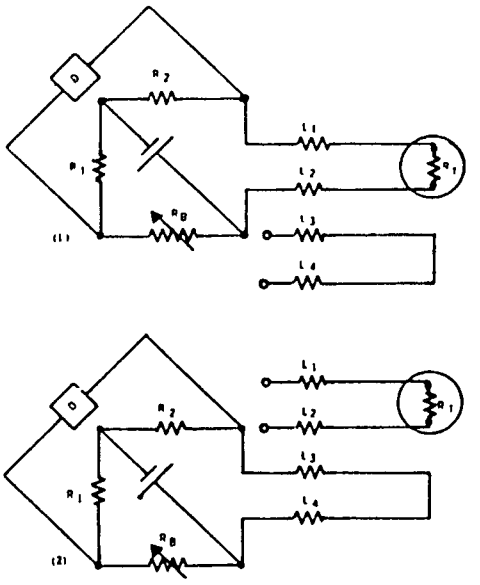
All of the main errors caused by DC systems are reversible and independent of the value of the measuring current. Thus by reversing the current and averaging the readings the effect of these errors could be eliminated. This is the principle of AC resistance measurement.

Figure 14.11 shows a simplified diagram of an AC resistance bridge. One arm of a Wheatstone bridge is replaced by a variable ratio transformer. The transformer turns-ratio is varied to obtain a bridge balance as determined by a null detector. When the bridge is balanced :

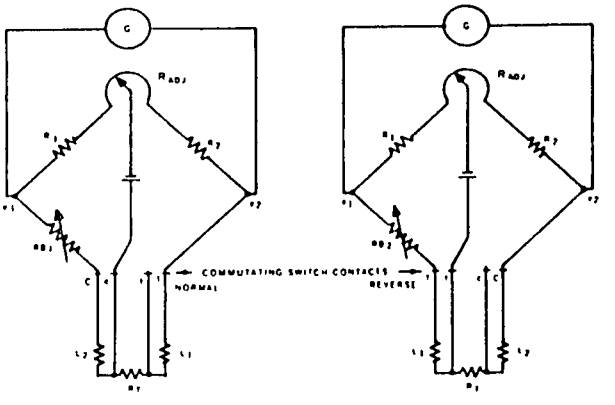
$$R_t = R_s\frac{N_2}{N_1} \qquad (14.8)$$



(a) A modified Wheatstone bridge for detrmining resistance of a three terminal thermometer



(b) Two-measurement method for measuring the resistance of a compensating loop four terminal thermometer



(c) Use of a Mueller Bridge to determine the resistance of a four terminal thermometer

Fig 14.10 –DC bridges for resistance measurement

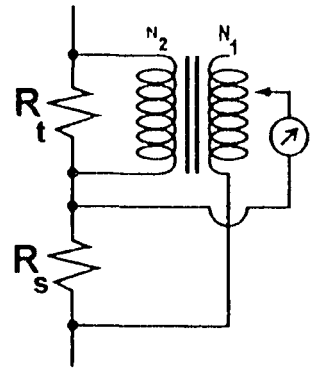


Figure 14.11 Simple schematic diagram of an AC bridge

The best AC bridges available today have uncertainties of the order of ±0.5 ppm of full scale reading .

c) DCC bridge

A further refinement in the resistance measurement process is to use a direct current comparator(DCC) bridge. These bridges can achieve sub ppm accuracy in resistance measurement. Both manual and automatic versions are available, though the automatic type is prohibitively expensive. The operation of a manually operated bridge is given below.

The direct-current-comparator bridge is a resistance bridge particularly suited for the comparison of 'low value" resistors and the scaling of low resistances under conditions in which each resistor functions at its own power level. In this bridge network, the ratio of the resistances is determined from a knowledge of the ratio of the currents flowing in the bridge resistors.

The direct-current- comparator, shown diagrammatically in Figure 14.12, provides a means for connecting together two isolated current sources with two resistors and the two ratio windings of the current comparator. The current comparator is a current ratio indicator based on the detection of zero flux in the magnetic core of the device. For direct current applications a double core magnetic modulator is used which consists of a double toroidal core magnetic modulator and a magnetic shield. The two ratio windings link the modulator and the magnetic shield which carries the currents to be compared. When the modulator output is zero the current ratio is equal to the turns ratio to a high degree of accuracy.

At ampere-turn balance, $N_x.I_x = N_s.I_s$. (14.9)

For a manually operated direct reading bridge a second bridge balance condition is necessary to make the resistance ratio result in a direct reading. This second balance is acheived by manually adjusting the number of turns N_x until the output from the bridge null detector is zero.

At the null voltage condition, V_d=O and $I_x.R_x = I_s.R_s$. When a flux and voltage balance is achieved it is clear that:

Rx = Rs.(Nx/Ns) .

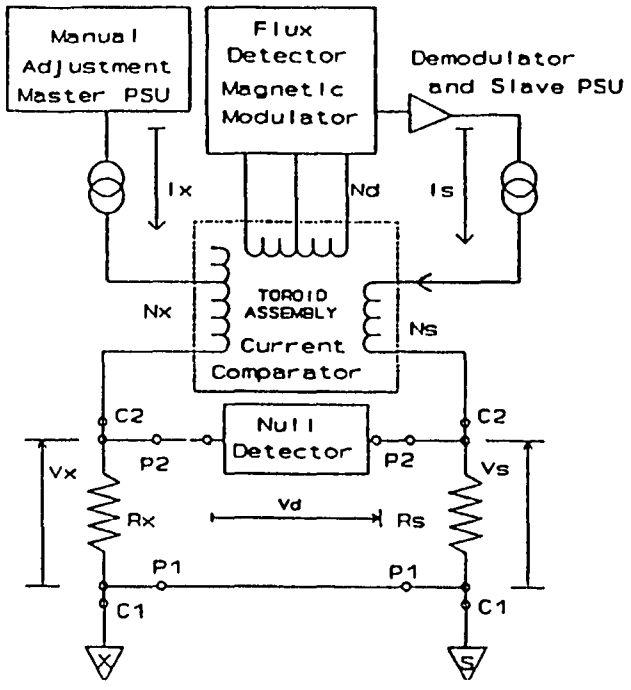


Fig 14.12 –Schematic of Direct Current Comparator bridge

14.7.2 Uncertainties of resistance thermometers

The uncertainties arise from a number of sources. The major sources are :

a) *Reference temperature* -The uncertainty of the reference temperature as measured by the reference thermometer and resistance measuring instruments.

b) *Calibration medium*- Temperature uniformity and stability of the calibration bath contributes an uncertainty component to the measured values. This is known as transfer uncertainty and is determined for each bath and included.

c) *Uncertainty in the fit*- If a comparison calibration is performed over a number of test temperatures, then an uncertainty component arises from the least squares fit used. This is estimated from the standard deviation of the residuals.

d) Hysteresis-The hysteresis of the test thermometer will contribute an uncertainty. This is estimated from the maximum difference of corresponding values displayed by the thermometer during increasing and decreasing calibration cycles.

e) *Self heating*-The effect of self heating of the thermometer due to the measuring current is taken into account as an uncertainty. For a 100 ohm PRT with a measuring current of 1mA this is of the order of 2 mK.

All of the above components are combined in quadrature to determine the combined standard uncertainty.

14.8 Calibration of thermocouples

14.8.1 The meaning of calibration

In calibrating thermocouples, the word 'calibration' can assume a number of different meanings; at least three different interpretations are possible. Frequently a thermocouple is calibrated to determine the deviation of its emf output in comparison to the tolerances specified for standardised letter designated thermocouple types (See Chapter 7,Table 7.3). This is known as conformance or type approval. Another meaning is the calibration done in situ. Not all applications will allow this but it is a better method. The third method is a step by step procedure only applicable to rare metal thermocouples, which have sufficient stability to

warrant this method. The basic principles of these methods are elaborated in subsequent sections.

14.8.2 Type approval

a) Reference equipment

A working standard thermocouple or platinum resistance thermometer is used as the reference standard. A WPRT can be used up to 1000 °C whereas a Pt/Rh standard thermocouple can be used up to 1200 °C.

Frequently a tube furnace or a stirred oil bath (Figure 14.3) or fluidized alumina bath and (Figure 14.4) is used to provide the thermally stabilsed medium. Temperature gradients within thermally stabilised furnaces or baths can be reduced or minimised by the insertion of a metal equalising block drilled with thermowells to receive the standard and test instruments. However such a block is not always necessary for example in multi-zone controlled furnaces.

b) Initial inspection

Thermocouples are available in various forms of insulation and protective sheathing as well as in 'bare-wire' form. Initial inspection will therefore depend upon their construction and use. Obvious signs of mechanical defects, contamination, etc. are recorded and the client informed if the laboratory feels that the validity or uncertainty of measurement in the calibration could be impaired. Any presence of moisture, particularly around compensating/extension lead connections, is investigated as this may reduce the leakage resistance and/or lead to the generation of emfs by electrolytic action. Measurement of the insulation resistance is a convenient method to identify any moisture within the thermocouple.

c) Heat treatment

Heat treatment/annealing of a thermocouple is a kind of 'adjustment'. A thermocouple to be calibrated is annealed at maximum immersion at the highest temperature of intended use. Type K thermocouples, which are subject to calibration changes on temperature cycling to 500 °C or above, are calibrated at increasing temperatures, and the first calibration point repeated at the end as a check. The same considerations apply to a lesser extent to other base-metal thermocouples.

Thermocouples are protected from contamination in the annealing furnace by inserting them in close fitting thin-walled recrystallised alumina tubes with closed ends. However, longer immersion may be needed to compensate for the poorer thermal coupling.

d) Immersion depth

Generally thermocouples are calibrated at the same immersion as required in normal use. However, thermocouples are immersed to a depth sufficient to overcome heat losses or gains at high and low temperatures, respectively. Such effects are induced by large diameter wires, thick walled insulators, and sheaths. Where possible a thermocouple is progressively immersed into a controlled calibration enclosure until further immersion shows no change in the measured emfs indicating that an appropriate immersion depth has been reached.

A steady emf may be obtained, but this does not necessarily mean that the correct temperature has been reached. Adequate immersion is only demonstrated if the change in emf on withdrawing the thermocouple one or two centimetres is small compared with the required uncertainty of measurement in the calibration.

e) Electrical measurements

Electrical measurements are normally made using digital voltmeters or direct reading temperature indicators. Manual switchgear and dials on selector switches, reversing switches and manual potentiometers are gently exercised on a daily basis through about twenty movements to clear oxide films and possible contact resistance.

Measurements are made of both forward and reverse polarities by means of a reversing switch to eliminate or minimise the effect of stray thermal emfs in the measuring system. Stray emfs can arise at any point in the measuring circuit where there is a change of temperature and at the juncture of dissimilar metals, e.g. copper wires and brass terminals. Suitable shielding and/or lagging and control of the ambient temperature should be provided. Digital voltmeters can behave differently in the positive and negative modes so instruments calibrated in both ranges should be used. The measuring circuit is checked (and corrected) for any residual emfs by measurement of the circuit emf when it is closed by short-circuiting at the thermocouple connection terminals.

14.8.3 In-situ calibration

In situ calibration is the most reliable method available for calibration of industrial thermocouples. This ensures that the immersion conditions in use are the same as those of the calibration.

14.8.4 Rare metal thermocouple calibration

Rare metal thermocouple calibration consists of a number of steps as given below:

h) Visual inspection
i) Conditioning and adjustment
j) Homogeneity test and
k) Intercomparison

Details of these procedures are given in Bibliography 14.3 and 14.6.

14.9 Calibration of solid block calibrators

14.9.1 Reference equipment

The temperature in the measurement zone of the temperature block calibrator is determined using a working standard platinum resistance thermometer (from -80 °C to +660 °C) or reference standard thermocouple (from +660 °C to +1300 °C).

14.9.2 Procedure

A complete calibration requires six determinations:

l) Deviation of the indication of the built-in controlling thermometer from the temperature in the measurement zone,

m) Axial temperature variation along the boring in the measurement zone,

n) Stability with time,

o) Temperature differences between the borings,

p) Temperature deviation due to heat conduction,

q) The influence of loading on the temperature in the measurement zone.

a) Determination of the deviation of the indication of the built-in controlling thermometer from the temperature in the measurement zone

Measurements

The determination of the deviation of the temperature given by the indicator of the block calibrator from the temperature in the measurement zone is performed in the central boring or in a particularly marked boring. Measurements at a minimum of three different temperatures (calibration points) are usually carried out; the test temperatures should be distributed as uniformly as possible over the required temperature range.

The deviation at each test point with increasing temperature as well as decreasing temperature is determined. The reading of the temperature display of the calibrator is recorded over a period of approximately 10 minutes for each test point. The average temperature at each test point (both on increasing temperature and decreasing temperature runs) is used to adjust the display temperature.

Evaluation

The values measured in the series at increasing and decreasing temperatures are averaged for each calibration point. The calibration result (deviation of the temperature measured with the standard thermometer from the indication of the calibrator) is documented in mathematical, graphical, or in tabular form.

b) Axial temperature variation along the boring in the measurement zone

Measurements

The greatest temperature difference occurring in the measurement zone of the central boring or in a particularly marked boring is determined.

The temperature is determined at the lower end, in the middle and at the upper end of the measurement zone, using a thermometer with a sensor length not exceeding 5 mm. The thermometer may be provided with a protective tube (outside diameter: d = 6 mm).

Example: The following measurements are required for a temperature block calibrator with a measurement zone 40 mm in length at the lower end of the boring:

a) Thermometer touching the ground;

b) Thermometer pulled out 20 mm;

c) Thermometer pulled out 40 mm; and

d) Thermometer touching the ground.

Measurements are carried out at the highest and at the lowest temperature of the measuring range. If one of these test points is at room temperature, the temperature for this measurement point is increased or decreased by 20 °C.

c) Temperature differences between the borings

The greatest temperature difference occurring between the borings is determined. To eliminate the influence of temperature variations with time, the temperature differences with respect to an additional test thermometer in the temperature block calibrator are determined.

The temperatures are determined in at least three borings distributed as uniformly as possible on the greatest reference circle of the temperature block.

d) The influence of loading on the temperature in the measurement zone

The influence of loading on the temperature in the measurement zone is determined by measuring the temperature difference between a reference thermometer and a test thermometer, when further borings are loaded with thermometers or suitable sheaths. The sheaths or thermometers should protrude from the respective boring by at least 200 mm. Maximum possible loading with thermometers/bushings of 6 mm or smaller in diameter should be ensured. The measurements are carried out at the temperature of the measurement range, which shows the greatest temperature difference with respect to room temperature.

e) Stability with time

The maximum range of temperatures indicated by a sensor in the measurement zone over a 30 minute period, when the system has reached equilibrium, is determined.

Measurements are performed at three different test temperatures: at the highest temperature of the measuring range, at the lowest temperature of the measuring range and at room

temperature. If the highest or lowest temperature corresponds to room temperature, the third test temperature is selected in the middle of the temperature range tested.

f) Temperature deviation due to heat conduction

In agreement with the client, the temperature error due to heat conduction is determined for such thermometers, which are to be calibrated at the client's. This deviation is not part of the temperature block calibrator's measurement uncertainty, but is to be taken into account separately when the temperature block calibrator is used. Temperature deviations due to heat conduction need not be taken into account for thermometers with outside diameters of d = 6 mm.

g) Uncertianty of measurements

The uncertainty to be stated as the uncertainty of the calibration of the temperature block calibrator is the measurement uncertainty with which the temperature in a boring of the calibrator can be stated. If the temperature deviation due to heat conduction may be neglected, this measurement uncertainty is to be equated with the measurement uncertainty a user can expect for a thermometer, when he calibrates this thermometer with the temperature block calibrator and complies with the operating instructions.

The main contributory factors to this uncertainty are:

r) The uncertainty of the temperature deviation shown by the indicator of the calibrator and
s) The uncertainty arising from the temperature distribution in the block.

The contributions to effect (a) come from the reference standard thermometer, and the resolution of the indicator of the calibrator. The method of computing the various contributions is illustrated by way of an example.

Example :

A calibrated platinum resistance thermometer is used to determine the temperature of one of the calibration borings of a temperature block calibrator having a built-in temperature indicator. The temperature indicated by the PRT is determined by measurement of its electrical resistance using an AC resistance bridge.

The uncertainty u_{tX} of the temperature t_X of the boring when the reading of the built-in temperature indicator is 250°C is given by:

$$u^2_{tX} = u^2_{tS} + u^2_{\delta tS} + u^2_{\delta tD} + u^2_{\delta ti} + u^2_{\delta tR} + u^2_{\delta tH} + u^2_{\delta tB} + u^2_{\delta tL} + u^2_{\delta tV} \qquad (14.10)$$

Where:

u_{tS} – uncertainty of the temperature of the reference thermometer derived from the ac resistance measurement,

$u_{\delta tS}$ – uncertainty of the temperature correction due to the ac resistance measurement,

$u_{\delta tD}$ – uncertainty due to drift in the value of the reference standard since its last calibration,

$u_{\delta ti}$ – uncertainty of the temperature correction due to limited resolution of the built-in temperature indicator,

$u_{\delta tR}$ – uncertainty due to temperature difference between borings,

eresis in the increasing and decreasing branches of the measuring cycle,

$u_{\delta tB}$ - uncertainty due to axial inhomogeneity of temperature in the borings,

$u_{\delta tL}$ - uncertainty due to the loading effect,

$u_{\delta tV}$ – uncertainty due to temperature variations during the time of measurement.

Uncertainties arising from stem conduction are not considered; the platinum resistance thermometer used as reference has an outer diameter of 6 mm. Prior investigations have shown that stem conduction effects can be neglected in this case.

a) **Reference standards (u_{tS}):** The calibration certificate of the resistance thermometer used as reference standard gives an expanded uncertainty of measurement, U = 20 mK (coverage factor k = 2) corresponding to the measured temperature value of 250.20 °C

b) **Determination of the temperature by resistance measurement ($u_{\delta tS}$):** The temperature of the resistance thermometer used as reference standard is determined as 250.20 °C. The standard uncertainty associated with the electrical measurement converted to temperature corresponds to ±15 mK.

c) **Drift of the temperature of the reference standard ($u_{\delta tD}$):** From general experience with platinum resistance thermometers of the type used as reference standard in the measurement, the change of the temperature due to resistance ageing is estimated to be within the limits of ±40 mK.

d) **Resolution of the built-in controlling thermometer ($u_{\delta ti}$):** The built-in controlling thermometer has a scale interval of 0.1 K, giving temperature resolution limits of ±50 mK with which the thermodynamic state of the temperature block can be uniquely set.

e) **Temperature difference between borings ($u_{\delta tR}$):** The calibrator has 6 holes. The largest temperature difference measured at 180 °C between the holes was 140 mK, leading to an assumed temperature distribution between the holes with limits of ±70 mK.

f) **Hysteresis effects ($u_{\delta tH}$):** The temperatures indicated show a deviation due to hysteresis. in cycles of increasing and decreasing temperatures which is estimated to be within ±50 mK.

g) **Axial inhomogeneity of temperature ($u_{\delta tB}$):** The deviations due to axial inhomogeneity of the temperature in the calibration boring have been estimated from readings for different immersion depths to be within ±250 mK.

h) **Block loading ($u_{\delta tL}$):** The influence of maximum loading on the temperature of the central hole was found to be 50 mK.

i) **Temperature instability ($u_{\delta tV}$):** Temperature variations due to temperature instability during the measuring cycle of 30 min are estimated to be within ±30 mK.

None of the input quantities are considered to be correlated.

Repeated observations: Due to the finite resolution of the indication of the built-in thermometer, no scatter in the indicated values has been observed.

Uncertainty budget

The uncertainty budget is given in Table 14.2

Table 14.2 –Uncertainty budget for block calibrator

Source	Estimate mK	Probability distribution	Standard uncertainty, mK	Sensitivity co-efficient	Uncertainty contribution,mK
Reference standards u_{tS}	20	Normal	10	1	10
resistance measurement $u_{\delta tS}$	15	Normal	15	1	15
Drift of reference standard $u_{\delta tD}$	40	Rectangular	23	1	23
Resolution of built-in thermometer $u_{\delta ti}$	50	Rectangular	29	1	29
Temperature difference between borings $u_{\delta tR}$	70	Rectangular	40	1	40
Hysteresis effects $u_{\delta tH}$	50	Rectangular	29	1	29
Axial inhomogeneity of temperature $u_{\delta tB}$	200	Rectangular	115	1	115
Block loading $u_{\delta tL}$	50	Rectangular	29	1	29
Temperature instability $u_{\delta tV}$	40	Rectangular	23	1	23
Combined standard uncertainty					137 mK

Expanded uncertainty

The expanded uncertainty associated with the measurement of the temperature of the calibrator is

$U = k \cdot u_{tx} = 2 \times 137\ mK = 0.27\ K$ (14.11)

Reporting of the result

The temperature to be assigned to the temperature sensing area of a thermometer inserted in one of the calibration borings when the built-in temperature indicator shows 250°C is 250.20 °C ± 0.27 °C.

The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor k = 2, which for a normal distribution corresponds to a coverage probability of approximately 95 %.

14.10 Calibration of temperature indicators and simulators

14.10.1 Calibration principles

a) Calibration of temperature indicator

The calibration of a temperature indicator is performed by applying electrical stimuli at the inputs of the indicator and by verifying that the outputs namely the indicated temperatures correspond to the applied stimuli.

A calibrated electrical source is substituted for the temperature sensor. Using reference tables, the electrical output of the temperature sensor at the required calibration point is determined and the output of the electrical source set to this level. This electrical signal is applied to the temperature indicator and the indicator's reading compared with the simulated input temperature.

b) Calibration of temperature simulator

A temperature simulator is an instrument which provides an electrical signal corresponding to an input setting in temperature units. The calibration principle is based on the verification of this conversion process by the direct measurement of the electrical signal produced by the simulator. The calibration is performed in accordance with appropriate standard reference tables.

In the calibration procedure the simulator is set at the required calibration point. The electrical output produced by the simulator at this setting is measured using a calibrated electrical measuring instrument. The measured value is converted into the equivalent temperature using reference tables and the deviation of the simulator setting determined.

14.10.2 Procedure

a) Reference standards and measurement configurations

The reference standards and the measurement configurations used for calibration of indicators and simulators are given in Table 14.3

The reference standards used in these calibrations must be calibrated and characterized for the effects of influence quantities over the applicable measuring range.

Table 14.3-Reference standard and measurement configuration for indicators and simulators

Instrument type	Sensor type	Reference standard	Measurement configuration
Indicator	Resistance Thermometer	Standard Resistors or Decade Resistor	Fig. 14. 13
Simulator	Resistance Thermometer	Ohmmeter	Fig. 14. 14
Indicator	Thermocouple (CJC on)	DC millivolt source,	Fig. 14. 15
Indicator	Thermocouple (CJC off)	DC millivolt source Reference thermocouple, Ice point reference	Fig. 14. 16
Simulator	Thermocouple (CJC on)	DC millivoltmeter	Fig. 14. 17
Simulator	Thermocouple (CJC off)	DC millivolt meter, Reference thermocouple, Ice point reference	Fig. 14. 18

b) Resistance indicators

In the case of resistance indicators, the method of connecting the reference resistance to the indicator will depend upon whether the indicator is intended to be used with a two-, three- or four-wire platinum resistance probes. Figure 14.12 shows the case where the indicator and the reference resistor are four terminal devices. Lead wires effects and influences from environmental conditions should be either corrected or/and included in the uncertainty budget. Good quality copper cable must be used to make connections.

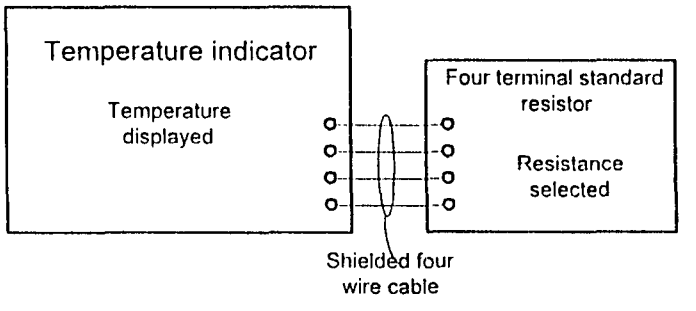


Figure 14.13 – Configuration for calibration of indicator of a resistance thermometer

c) Resistance simulator

The method of connecting the reference ohmmeter to the simulator will depend upon whether the simulator output is configured to simulate a two-, three- or four-wire platinum resistance probe. Fig. 14.14 shows the case where the simulator and the reference ohmmeter are four terminal devices.

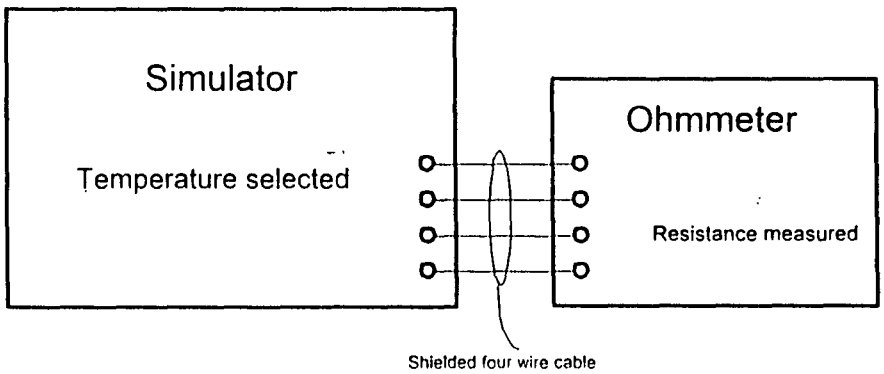


Figure 14.14 – Configuration for calibration of resistance simulator

d) .Thermocouple indicator (with CJC)

The measurement configuration for calibration of thermocouple indicators with cold junction compensation is shown in Figure 14.15.

When an indicator having cold junction compensation is to be calibrated, thermocouple wires or extension cables are used to connect the indicator to the external reference cold junction. The cables or wires have to be calibrated over a suitable temperature range in the vicinity of the normal laboratory temperature and the corrections to these elements will be taken into account in the measurement process or in the uncertainty estimation.

The choice of the thermocouple wires or extension cables depends on the type of thermocouple considered. To calibrate thermocouple wires (or extension cable), one method is to manufacture a thermocouple with these wires and to calibrate it using normal procedures over a limited range (0 C to the temperature of the indicator terminals). The correct polarity of the thermocouple connections should be observed.

Suitable attention must be given to the electrical insulation of the reference thermocouple. Precautions are taken to eliminate or minimize the effects of spurious emfs in the measuring circuit

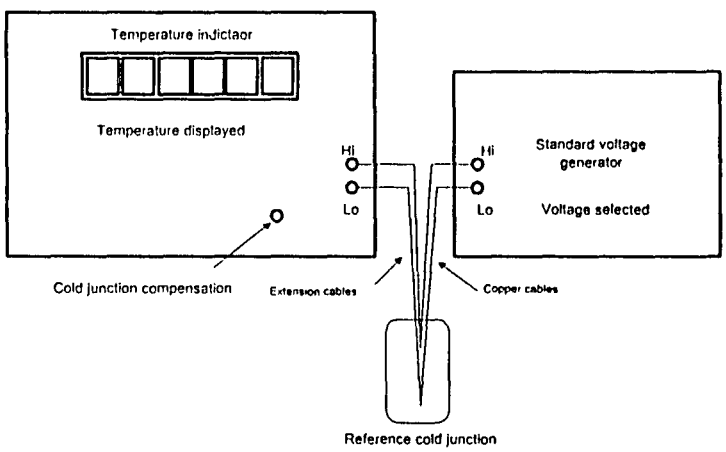


Figure 14.15-Configuration for calibration of thermocouple indicator (with CJC)

e) Thermocouple indicator (without CJC)

The measurement configuration for calibration of thermocouple indicators without cold junction compensation is shown in Figure 14.16. Copper wires are used to connect the voltage generator to the indicator.

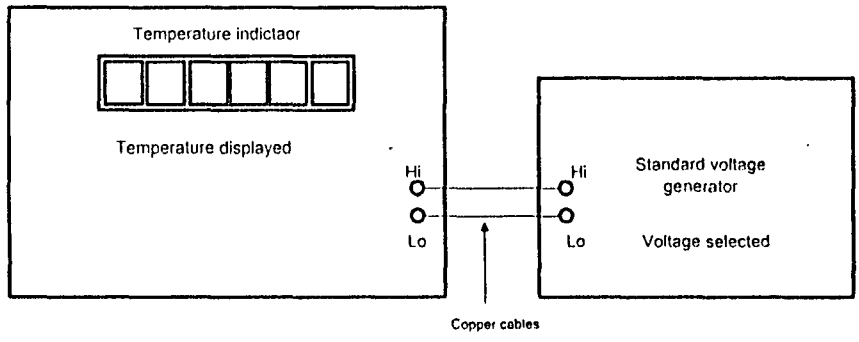


Figure 14.16-Configuration for calibration of thermocouple indicator (without CJC)

f) Thermocouple simulator (with CJC)

The configuration for the calibration of a thermocouple simulator with cold junction compensation is shown in Figure 14.17.

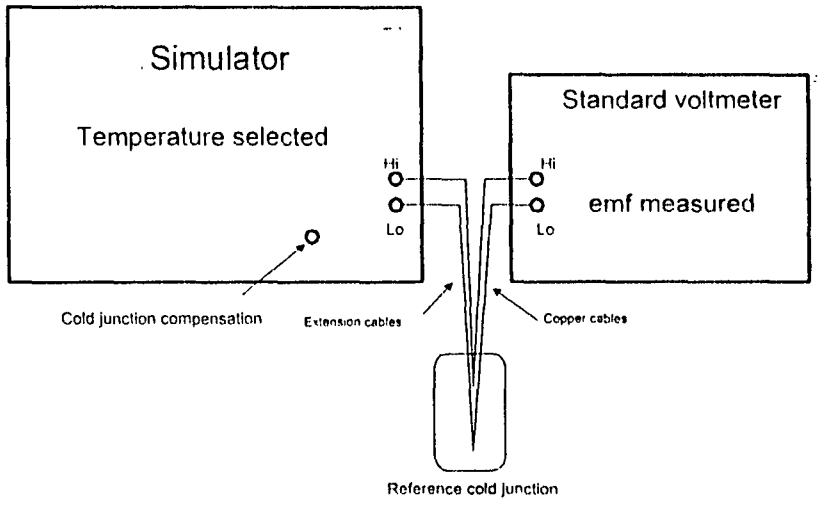


Figure 14.17-Configuration for calibration of a thermocouple simulator (with CJC)

g) Thermocouple simulator (without CJC)

The configuration for the4 calibration of a thermocouple simulator without cold junction compensation is shown in Figure 14.18.

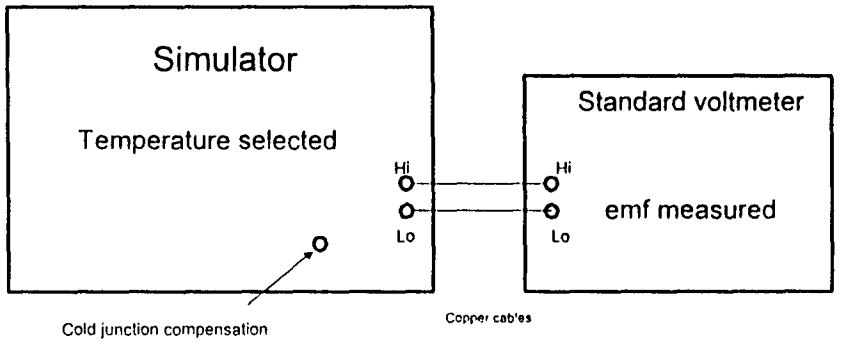


Figure 14.18-Configuration for calibration of a thermocouple simulator (without CJC)

h) Reference junction

There are several ways to realise an accurate reference junction temperature. One way is to locate the thermocouple's reference junction in an environment with a very stable and well defined temperature. For example, a well prepared physical ice point, provides a stable temperature of 0 °C with a typical standard uncertainty of 2,5 mK.

Alternatively, a large well-insulated copper block at ambient temperature can be used, provided that the block's temperature is measured using an external standard thermometer. An alternative to a physically realised reference temperature is the use of an automatic reference junction device which is an electronic compensation circuit. Such a device must, of course, itself be calibrated before use.

Appendix 1-Constants for reference functions of ITS-90 in the range 0 °C to 961.68 °C

A_0	-2,135 347 29	B_0	0,183 324 722
A_1	3,183 247 20	B_1	0,240 975 303
A_2	-1,801 435 97	B_2	0,209 108 771
A_3	0,717 272 04	B_3	0,190 439 972
A_4	0,503 440 27	B_4	0,142 648 498
A_5	-0,618 993 95	B_5	0,077 993 465
A_6	-0,053 323 22	B_6	0,012 475 611
A_7	0,280 213 62	B_7	-0,032 267 127
A_8	0,107 152 24	B_8	-0,075 291 522
A_9	-0,293 028 65	B_9	-0,056 470 670
A_{10}	0,044 598 72	B_{10}	0,076 201 285
A_{11}	0,118 686 32	B_{11}	0,123 893 204
A_{12}	-0,052 481 34	B_{12}	-0,029 201 193
		B_{13}	-0,091 173 542
		B_{14}	0,001 317 696
		B_{15}	0,026 025 526

C_0	2,781 572 54	D_0	439,932 854
C_1	1,646 509 16	D_1	472,418 020
C_2	-0,137 143 90	D_2	37,684 494
C_3	-0,006 497 67	D_3	7,472 018
C_4	-0,002 344 44	D_4	2,920 828
C_5	0,005 118 68	D_5	0,005 184
C_6	0,001 879 82	D_6	-0,963 864
C_7	-0,002 044 72	D_7	-0,188 732
C_8	-0,000 461 22	D_8	0,191 203
C_9	0,000 457 24	D_9	0,049 025

15 Calibration of electrical standards and test instruments

15.1 Introduction

General guidelines for calibration of electrical measurement standards and test instruments are given in this chapter.

15.2 General conditions

The general features applicable to the calibration of all electrical standards and instruments are given in the following sections.

15.2.1 Reference standard

The hierarchy of calibration standards used for calibration of electrical measuring instruments and components is given in Figure 15.1.

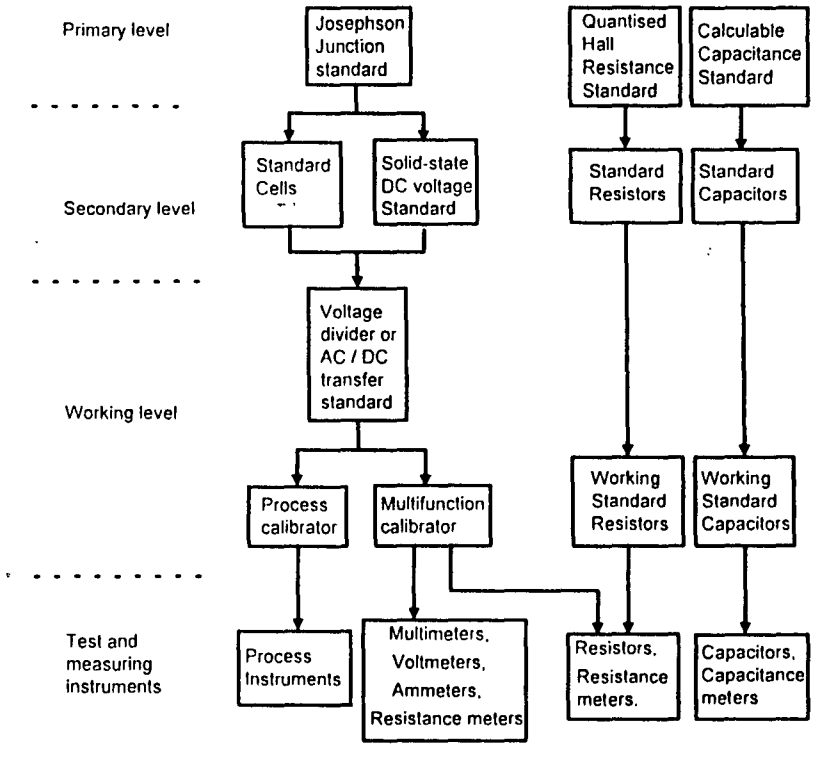


Figure 15.1 Hierarchy of electrical measurement standards

This diagram can be used as a guide for deciding on the next higher level standard against which a given unit should be calibrated. Primary standards are those described Part 1(Chapter 8), namely the Josephson voltage standard, the Hall resistance standard and the calculable capacitance standard. Secondary standards are those calibrated against the primary standards, namely standard cells and solid-state DC voltage standards, secondary standard resistors and secondary standard capacitors.

Working standards are the AC/DC transfer standard, voltage divider, multifunction calibrator, process calibrator, working standards of resistance, and working standards of capacitance and a number of other equipment used as secondary standards for different parameters.

15.2.2 Adjustments in calibration

If the technical manual of the instrument is available with the adjustment potentiometers and trimmers clearly identified then it is possible to adjust the instrument to give minimum deviations. The adjustment is usually done at the middle of the scale or at a designated voltage or current level indicated in the manual. If the technical manual is not available then the deviations are recorded in a test report and corrections should be applied when using the instrument. However this is hardly possible for instruments used in the field. As a general rule, instruments that are found to be out of specification and cannot be adjusted should be either rejected or clearly marked as "Out of Specs" .

15.2.3 Reference conditions

The reference temperature for electrical calibrations is 23 ± 1 °C. A low relative humidity of around 40 –50 per cent is necessary since high humidity levels affect electrical components. One of the most important requirements would be to have an environment with minimal electrical and electromagnetic interference.

15.2.4 Closed case calibration

The ability to calibrate a digital multimeter (DMM) using internally stored offset and gain corrections is known as closed case calibration. A significant number of present day digital multimeters (DMMs), particularly bench and laboratory types, have the ability to be calibrated in the closed case mode. All major manufacturers now provide closed case calibration facilities in their top of the range instruments.

There is a common misconception that instruments having closed case facility do not require calibration using external standards. This is not correct. In order to determine the corrections that are stored internally, a known set of values have to be applied at the input of the instrument. These known values could only be obtained from an external standard.

15.2.5 Closed loop calibration

A system that enables the measurement of an instrument performance, and its automated closed case adjustment is known as a closed loop calibration system. The main components of a closed loop system are the unit under test (UUT), a device to provide the calibration stimuli such as a multifunction calibrator and a computer, interconnected using the IEEE 488 interface bus.

The computer is programmed to address the unit under test through the interface bus and conduct the calibration. It takes the as-found test data, analyses the results and adjusts the unit under test as required. The unit under test of course must be able to be adjusted without manual operator intervention i.e. having the closed case calibration facility. The majority of closed loop calibrations involve digital multimeter(DMMs) , since their readings can be transferred easily to a computer for evaluation.

15.3 Calibration of multifunction calibrator

15.3.1 General features

There are two aspects to calibration, verification and adjustment. These are used to determine and correct for the classes of errors that a calibrator can exhibit. In some environments the item to be calibrated is verified when it is returned to the calibration laboratory at the end of the recalibration cycle and when it leaves the laboratory after it has been adjusted. These two verifications are sometimes referred to as *as-found* and *as-left* calibration.

a) Verification of calibrator

During verification, the calibrator's outputs on each range and function are verified by comparison to known standards but are not adjusted. A comprehensive set of measurement standards is usually required to perform these tests.

b) Adjustment of calibrator

The adjustment of the calibrator is undertaken when the outputs are found to be outside of the specification limits. There are three available methods of adjustment:

Artifact calibration adjustment

Software calibration adjustment, and

Manual calibration adjustment.

The most advanced of these techniques is artifact calibration. It uses a small number of single-valued artifacts to provide a fully traceable calibration using a complement of calibration standards. The calibrator's microprocessor senses the difference between its output and the standard value and stores it in firmware. This is applied as correction to the calibrator's output.

Software calibration is done in much the same way as a manual calibration. A correction factor for its outputs on each range and function is obtained by comparison to external standards. During operation, the microprocessor applies this correction factor to the calibrator outputs. e.g. Fluke 5440 B and 5450 A models are adjusted using this technique.

In a manual adjustment, the calibrator outputs are adjusted against external standards through internal controls. The Fluke 5100B and other earlier models are adjusted in this manner. The exact procedure of calibration of a multifunction calibrator is dependant on the model of the instrument. General principles applicable to present day instruments are given in the next four sections.

15.3.2 DC voltage range

a) Standard equipment

A DC voltage standard (e.g Fluke 734A) and a voltage divider are required for the calibration of the DC voltage range up to 1000 V.

b) Principle

The principle of the method is to compare the DC voltage output of the calibrator with the output of a DC voltage standard such as the Fluke 732 A. Since the output of a DC voltage standard is approximately 10 volts, a reference divider is used to divide the output of the calibrator. A null detector is used to compare the two voltages.

c) Procedure

The equipment is connected as shown in Figure 15.2. All equipment are switched on and left for about 30 minutes for warm up.

The reference divider is set to the lowest voltage level e.g 0.1 V. The calibrator output is set to the value obtained by dividing the certified value of the DC voltage standard by the certified value of the appropriate ratio of the reference divider. e.g if the Certified value of the DC standard is 9.999 95 V and the value of the 100:1 ratio of the divider is 100.000 03 , the divider output will be 9.999 95/100 .000 03 = 0.09999470 V=99.99470 mV. If the calibrator output is set to this value the null detector should read zero. If the null detector gives a finite deflection the output of the calibrator is adjusted until the null detector is balanced to within 0.0 ± 0.1 μV. The calibrator display is recorded. The correction to the calibrator value would be the difference between the displayed reading and 0.099 99470 V.

The procedure is repeated for each DC voltage range of the calibrator. However, the ratio of the divider should be 10:1 for 1 V and 100 V outputs and 100:1 for 100 V output. For 10 V output an exact ratio of 1 is used.

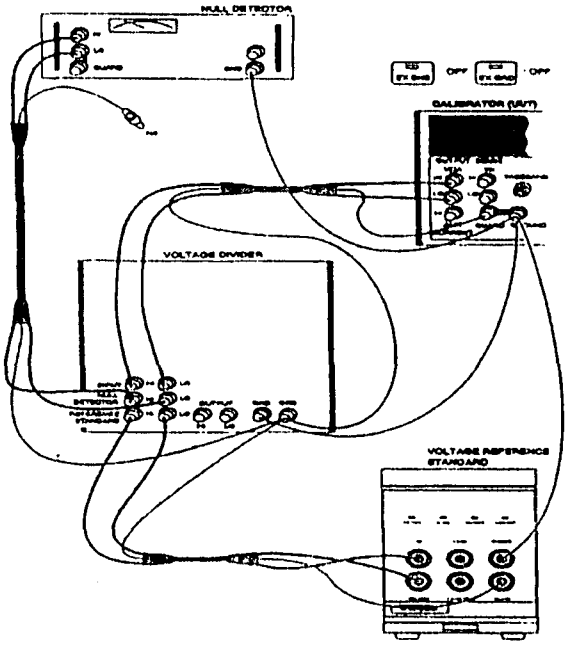


Figure 15.2 –DC voltage measurement setup

15.3.3 DC current range

a) Standard equipment

A calibrated digital multimeter of at least 8 1/2 digit display and a set of standard resistors ranging from 0.01 Ω to10 kΩ are required.

b) Principle

The current calibration is carried out by measuring the voltage across a known standard resistance when output current of the calibrator is passed through the resistance.

c) Procedure

The equipment are connected as shown in Figure 15.3. All equipment are switched on and left for about 30 minutes for warm up. The calibrator output is set to the mid range of each DC current range. An appropriate four terminal resistance standard is connected as the current shunt. The DC voltage across the resistance standard is measured using the calibrated digital voltmeter. The current passing through the resistance is calculated by dividing the measured voltage by the certified value of the resistance standard. e.g At the mid point of the 0-330 μA DC current range of the calibrator, namely 100 μA (0.1 mA) a 0.01 Ω standard resistance is used.

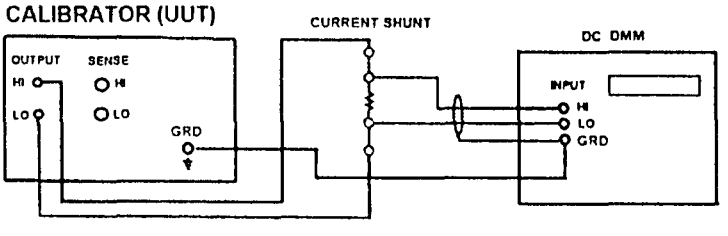


Figure 15.3-DC current measurement setup

Table 15.1 shows a typical tabulation of the measurement data.

Table 15.1- DC current measurement worksheet

Calibrator range	Calibrator Output	Std. resistance value	DMM reading	DMM correction	Corrected DMM reading	Calculated current
11 A	10.000 00 A	0.00999874 Ω	99.99791 mV	+0.06 µV	99.9949700 mV	10.0007571 A
2.2 A	1.000 000 A	0.099 998 7 Ω	99.99790 mV	+0.07 µV	99.99797000 mV	0.9999927 A
220 mA	100.000 0 mA	9.999 985 Ω	0.9999956 V	+0.1 µV	1.00005600 V	100.00575 mA
22 mA	10.000 00 mA	100.000 15 Ω	1.000003 5V	+0.1 µV	1.00010350 V	10.00102 mA

15.3.4 AC voltage range

a) Standard equipment

An AC/DC transfer standard (e.g Fluke 792 A), and a 8 ½ digit (eg HP 3458) digital multimeter are required for the calibration of the AC voltage range up to 1000 V.

b) Principle

The AC voltage ranges of the UUT are compared with the calibrated DC voltage ranges (Section 15.3.2) using the AC/DC transfer standard and the digital multimeter.

c) Procedure

1. The equipment is connected using low thermal leads as shown in Figure 15.4.
2. The calibrator is switched on and allowed to warm up for the time interval indicated in the manual.
3. The range of the AC/DC transfer standard is set to the appropriate range. (e.g for 1V input ,set it to 2.2 V range)
4. Set the calibrator to 1 V DC source, internal sense and operate. (See Table 15.2)
5. Allow at least 60 s to stabilise, and record the DMM reading. (+ scale).
6. Reverse the polarity of the 1 V DC source, record the DMM reading again (-scale).
7. Average the readings (+ scale and –scale) and use the average value. e.g if the + scale reading is 1.000 032 V and –scale reading is 1.000 012 V, the average reading to use is 1.000 022 V.
8. Set the calibrator to 1 V at 1 kHz and put the calibrator on operation mode.
9. Adjust the output of the calibrator to obtain the same average reading on the DMM, as that of step 7.
10. Allow the DMM reading to be stabilised and record the DMM reading.
11. Repeat steps 3 to 10 for each range and frequency as indicated in the manual.

Table 15.2 shows a typical tabulation of the measurement data.

Table 15.2-AC voltage measurement worksheet

UUT range	UUT frequency kHz	UUT setting V	UUT display AC V	UUT Relative error ppm	AC/DC transfer error ppm	Corrected AC error ppm
2.2 V	1	1	0.9999982	-1.8	-2	-3.8
22 V	1	10	9.99998	-20	-1	-21
220 V	1	100	99.99985	-150	-9	-159
1000 V	1	1000	999.9999	-100	-11	-111

NOTE : Column 4 gives the displayed AC voltage output of the calibrator, equivalent to the average DC DMM reading. The AC/DC transfer error is obtained from the calibration certificate of the AC/DC transfer standard.

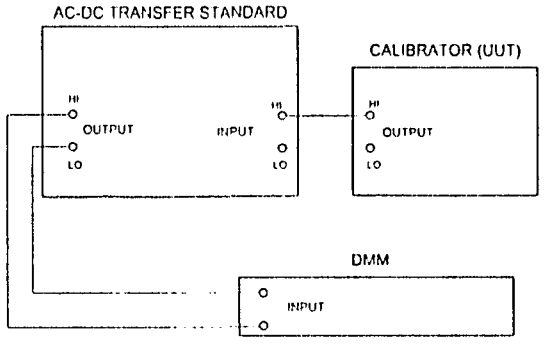


Figure 15.4-AC voltage calibration set up

15.3.5 AC current range

a) Standard equipment

An AC/DC transfer standard(e.g Fluke 792 A),8 ½ digit digital multimeter (e.g HP 3458), AC current shunt and shunt adaptor are required for the calibration of the AC current range up to 20 A.

b) Principle

The AC current ranges of the UUT are compared with the calibrated DC current ranges (Section 15.3.3) using the AC/DC transfer standard, current shunt, shunt adaptor and the digital multimeter.

c) Procedure

1. The equipment is connected using low thermal leads as shown in Figure 15.5.
2. The calibrator is switched on and allowed to warm up for the time interval indicated in the manual.
3. Select the appropriate current shunt and set the range of the AC/DC transfer standard to 700 mV.
4. Set the calibrator to 1 A DC source.
5. Allow at least 60 s to stabilise, and record the DMM reading. (+ scale).
6. Reverse the polarity of the 1 A DC source, record the DMM reading again (-scale).
7. Average the readings (+ scale and –scale) and use the average value. e.g if the + scale reading is 1.000 006 V and –scale reading is 1.000 004 V, the average reading to use is 1.000 005 V.

8. Set the calibrator to 1 A at 40 Hz and put the calibrator on operation mode.
9. Adjust the output of the calibrator to obtain the same average reading on the DMM, as that of step 7.
10. Allow the DMM reading to be stabilised and record the DMM reading.
11. Repeat steps 3 to 10 for each range and frequency as indicated in the manual.

Table 15.3 shows a typical tabulation of the measurement data.

Table 15.3-AC current measurement worksheet

UUT setting	Frequency	UUT reading	UUT relative error,ppm	AC/DC transfer error of shunt,ppm	Corrected relative error,ppm
1.000 00 A	40 Hz	0.9999985 A	1.5	+15	+16.5
1.000 00 A	500 Hz	0.9999981 A	1.9	+12	+13.9
100.000 mA	40 Hz	99.99984 mA	1.6	+14	+15.6
100.000 mA	10 kHz	99.99982 mA	1.8	+12	+13.8

NOTE: Column 3 gives the displayed AC current output of the calibrator, equivalent to the average DC DMM reading. The AC/DC transfer error is obtained from the calibration certificate of the current shunt. (This usually includes the AC/DC transfer error of the transfer standard).

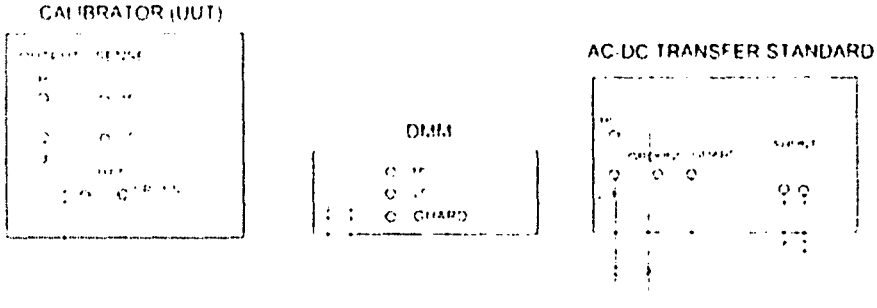


Figure 15.5-AC current calibration set up

15.4 Calibration of analogue multimeters

Analogue multimeters are rather rare now. However a few basic principles used in their calibration are included:

15.4.1 Zero adjustment

The zero of an analogue multimeter is adjusted with the use of a screwdriver. Care must be taken not to exert any undue force on the movement, as this would damage the fine spring attached to the moving coil.

15.4.2 Voltage and current ranges

The voltage and current stimuli are obtained from a voltage or current calibrator or multifunction calibrator. Three positions of each voltage and current range need to be

verified. Usually readings are taken in the lower end, middle and higher end of the scale. At least three readings at each position should be taken and the mean value worked out.

15.4.3 Resistance ranges

Resistance ranges are verified using the resistance references of a multi function calibrator or by connecting working standard resistors at the terminals of the multimeter. However adjustment of the resistance ranges of an analogue multimeter is quite difficult as the scales are not linear especially at the higher end of the scale.

15.6 Calibration of digital multimeters

There are a large variety of digital multimeters, the main types being hand held, bench and laboratory types. All these types are calibrated using a multifunction calibrator although in the case of the laboratory type multimeters special precautions have to be taken as the test uncertainty ratio approaches 1:1.

15.4.4 Handheld type

The hand held digital multimeter is the most commonly used type and typically has 3 ½ or 4 ½ digit display with five electrical functions, AC-DC voltage, AC-DC current and resistance. Most models also have frequency, continuity, diode test, and capacitance and waveform functions. A few enhanced models also have large LCD panels with graphics display ability. These instruments require regular calibration generally once in six months or a year depending on usage and the particular model.

15.4.5 Bench type

Bench type digital multimeters are used in many electronic workshops and test installations. These usually have 4 ½ or 5 ½ digit displays and lower uncertainties than the hand held type. These also have five electrical functions and additional functions of frequency, capacitance, thermocouple inputs etc. depending on the model. Some models also have RS 232 or IEEE 488 interfaces enabling them to be calibrated in closed loop configuration.

15.4.6 Laboratory type

Laboratory type is the most accurate type of digital multimeter available and their uncertainties approach those of the multifunction calibrator. These generally offer five functions AC-DC voltage, AC-DC current and resistance and are available with upto 8 ½ digit display.

Laboratory type digital multimeters contain microprocessors and memory chips that allow them to perform complex mathematical computations and store corrections on all functions and ranges. These instruments are often calibrated in automated closed loop mode using their IEEE-488 interfaces.

a) General calibration techniques

Detailed calibration procedures are beyond the scope of this manual. It is very important to follow the procedure indicated in the technical manual in performing the calibration of a particular instrumentDigital multimeters of all types basically consist of two main sections, the measurement section and the control section as shown schematically in Figure 15.6.

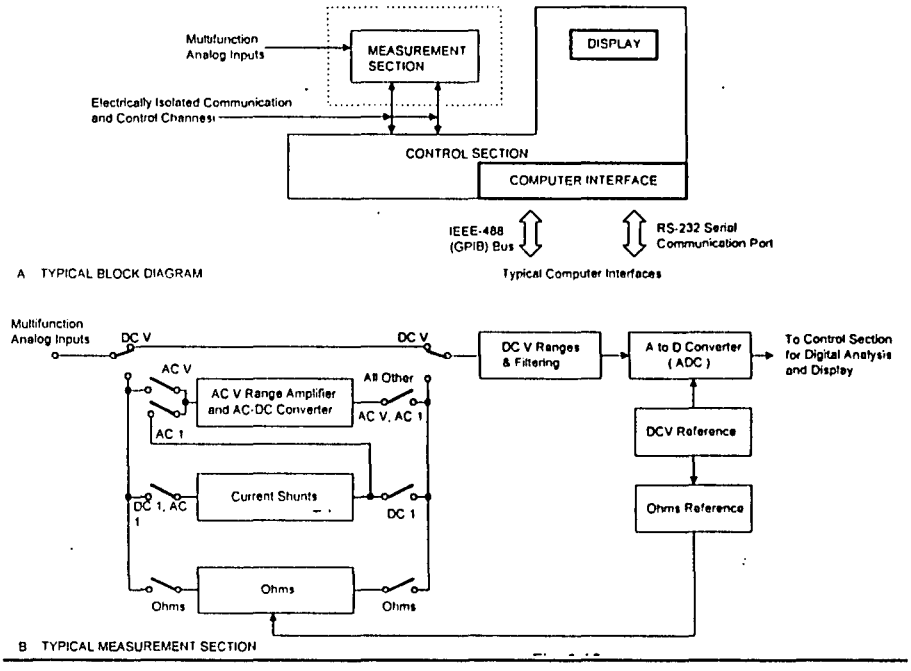


Figure 15.6 Sections of a digital multimeter (Source: Fluke Corp., U.S.A)

The measurement section is made up of the analogue conditioning circuits and analog-to - digital converter. The control section consists of a microprocessor, memory and associated circuitry. The measurement section requires verification and calibration adjustment. The control section requires no calibration adjustment as it is usually checked internally on power up.

The sections that require calibration adjustment are :

b) Internal references

These are internal dc voltage references and resistance references. In many instances a direct measurement of the DC voltage reference or resistance reference is not required. Instead a known input voltage or resistance is applied at the input and adjustment is made until the instrument displays the applied input voltage or resistance.

c) Analogue-to digital converter (ADC)

Since all functions use the ADC, it must be calibrated as one of the first steps. Some digital multimeter calibration schemes call out separate ADC and reference calibrations; other schemes merely call out dc voltage range calibrations only. Digital multimeters whose procedures do not call out separate ADC adjustments do have internal corrections. The calibration procedure simply calls for an adjustment in the straight-in dc voltage range first. This range, going directly into the ADC, has unity gain and thus has no significant error in scale factor. The calibration procedure will often call for a zero offset adjustment of the dc range, and then the ADC is adjusted

d) DC voltage range

Digital multimeters usually have full-scale ranges of 200 V dc, 300 V dc, or 1000 V dc, typically divided by factors of 10 to determine the lower ranges. Normal calibration practice limits the testing of ranges to just less than full scale. This is because most digital multimeters are auto ranging, and will go to the next higher range if the input is a certain percentage of full scale. So the calibration voltages for a digital multimeter with full-scale range of 200 V dc usually follow a 190 mV, 1.9 V, 19 V, 190 V sequence upto 1000 V dc. Modern multifunction calibrators take advantage of this structure.

The zero on each range may also need to be adjusted. The calibration procedure is to apply a short circuit to the input to the amplifier and adjust the digital multimeter reading to exactly zero volts dc. This would be followed by an input near full scale, in this case, 190 mV, dc. The digital multimeter is then adjusted to display the exact input voltage. In effect, the user is making the gain exactly 100. A digital multimeter calibration may also require an input of opposite polarity, -190 mV. This is to correct either for secondary linearity errors of the range amplifier, or for linearity errors within the ADC.

e) AC-DC converter

AC-DC converter calibration is similar for all types of converters. Amplitude adjustments are often made at two or more frequencies on each range. Zero adjustments are not usually made.

f) Average Responding AC-DC Converters

Calibration adjustment of average responding converters corrects for deviations in the equation y = mx+ b. However, the b term is solved not for inputs at zero volts, but typically for inputs at 1/10 th or 1/100 th of full scale. This is because precision rectifiers tend not to work well at zero volts input. Near zero volts, they rectify noise that would otherwise ride on the input waveform and average to zero. By moving the b term calibration off of zero, this problem is avoided.

g) True RMS AC-DC Converters

True rms converters need similar calibration of ranges at full-scale and at near-zero input levels. But true rms circuits have an even greater problem near zero volts than average responding converters. For example, analog log/antilog schemes employ a precision rectifier, resulting in noise rectification problems like those associated with an average responding converter. Also, since the displayed output voltage is the root mean square voltage of the signal and noise voltages, very small input signals cause the noise voltage to dominate. Consequently, true rms calibrations are accomplished with inputs well above zero volts.

There are additional adjustments to correct for errors in linearity of rms converters. If the digital multimeter has a dc-coupled ac voltage function, there may be zero input adjustments to correct for offset errors of the scaling amplifiers.

The ac voltage converter can have a separate calibration for the true rms converter, but often its calibration is combined into the main ac voltage function calibration. For example, if the true rms module can handle a 2 V full-scale waveform, the 2 V ac range should be calibrated first; then adjust the true rms module. The other ranges are then adjusted to correct for their gain errors. In some cases, the true rms module needs more than two different inputs to correct for linearity errors. For example, an ac voltage calibration adjustment may call for inputs of 19 mV; 190 mV and 1.9 V on the 2 V range.

Scaling sections, averaging converters, and true rms converters have resistive and capacitive errors. A major consideration when calibrating ac voltage is frequency response. The general requirement is to use a constant-amplitude calibrator that covers the entire frequency range of the digital multimeter. The conversion takes some time, and slewing through the pass band is time consuming. Because of this, spot frequency checks are usually made instead.

Low frequency calibration is generally performed at 400 Hz to 1 kHz. The high frequency adjustments are done afterwards. The frequencies used for high frequency adjustments are largely determined by the capacitive vs. resistive characteristics of the scaling circuits. When making a high frequency adjustment, one of two actions is performed:

.The actual frequency response of a scaling amplifier or attenuator is physically adjusted.

The digital multimeter's frequency response at cardinal points is stored in its non-volatile memory. The digital multimeter firmware then displays the correct reading at any frequency by interpolating between frequency points.

The second method requires a digital multimeter with an internal frequency counter to determine input frequency.

h) Resistance Converter Calibration

Calibration of resistance converters generally consists of zero and gain adjustments. For example, each range of the digital multimeter's resistance function is first corrected for proper zero reading. Then a near-full-scale input is applied to each range, and adjustments are made if necessary.

When calibrating digital multimeters with 4-wire resistance capability, resistance sources should have remote sensing capability (e.g. as provided in Fluke 5450A Resistance Calibrator or Fluke 5700A multifunction calibrator).

In the 2-wire set up, the sense path and ohms current path are on the same set of terminals. Resistance errors due to the connecting leads, can be significant. In general, proper connection of 2-wire resistance calibration for a meter with even 100 mΩ resolution can be a problem. (e.g. In the Fluke 5700A this problem has been addressed by incorporating a 2-wire ohms compensation feature).

Separate 2- and 4-wire resistance calibrations could be specified in calibration procedures. Since the 4-wire sense path is the same as the dc voltage signal conditioning path, all that is required is to correct the gain of the current source for resistance converters with current sources. However, second-order effects cause discrepancies in apparent gain when the dc voltage amplifiers are configured to sense either a dc voltage input directly or the voltage across the unknown resistor. Because of this, many of the higher precision digital multimeters require calibration for the 2- and 4-wire resistance.

i) Calibration of current converters

Both ac and dc current converters are calibrated by applying a known current and adjusting for the correct reading. Direct current converters correct for zero and gain; alternating current converters correct for down-scale and full-scale response. Typically, there are no high frequency adjustments for alternating current, primarily because current shunts are not inductive enough to cause significant errors relative to the digital multimeter's specifications.

15.5 Calibration of resistors

15.5.1 Secondary standard resistors

The primary standard for resistance is the Quantum Hall Effect resistance standard. Specialised potentiometers and null detectors are used to transfer the value of R_h into a standard resistor. In the transfer the laboratory resistor and the longitudinal plane of the QHE semiconductor are series connected so that the current I flows through both of them, Figure 15.7. The discrete resistor R is given by :

$$R = R_h \frac{V_r}{V_h}$$

R_h-Quantum Hall resistance

V_h-Hall voltage (See section 8.2.3, Chapter 8 for their definitions)

The current flowing through the Hall bar and test resistor, I, is approximately 25 to 37 μA. In order to avoid leakage effects in the overall test system, discrete resistors of value 6400 Ω or 12 900 Ω are used. The value of the discrete test resistor is transferred to the 1 Ω and 10 kΩ artifact standards.

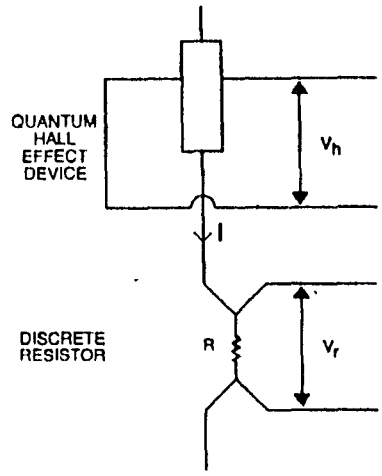


Figure 15.7 –Transfer of resistance from Hall bar to discrete resistor

15.5.2 Working standard resistors

a) AC and DC methods

Basically two different approaches can be taken for the calibration of resistors, namely DC calibration or AC calibration.

In DC calibration the resistors to be compared are connected in a circuit with a DC current or voltage source. The excitation current is DC and therefore the measurement does not include effects due to inductance and capacitance. A Wheatstone bridge (Figure 15.8) or a Kelvin double bridge(Figure 15.9) is usually used for less accurate work. For sub ppm accuracy a DCC bridge can be used.

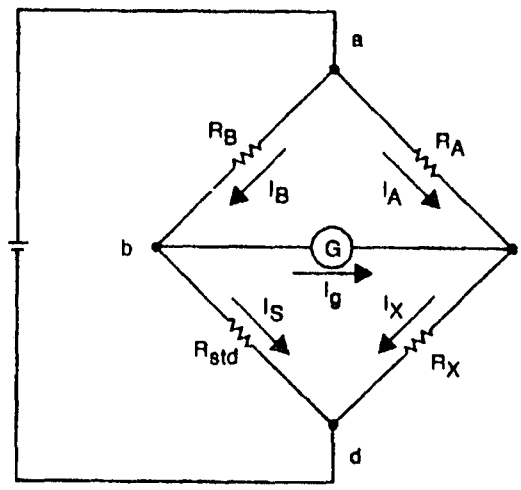


Figure 15.8-Wheatstone bridge

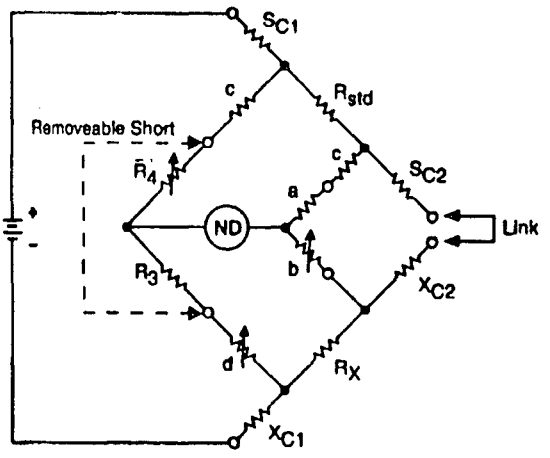


Figure 15.9-Kelvin double bridge

In AC calibration, an AC voltage source is used for excitation of the measuring circuit, usually this is an accurate AC bridge.

A potentiometer can be used for both DC and AC calibrations. The principle is illustrated in Figure 15.10.

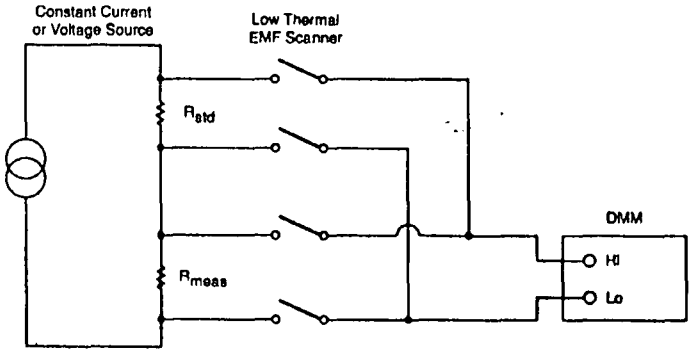


Figure 15.10-Potentiometer method for comparison of resistors

This method can be applied for resistors of 1 Ω to10 kΩ. In this method a constant and stable voltage is maintained across the two resistors. The voltage across each resistor is measured using an accurate digital multimeter.

b) Unbalanced-bridge circuit for six resistors.

An automated system, based on an unbalanced-bridge technique, used by NIST to calibrate resistors of nominal decade values of 1 kΩ, 10 kΩ, 100 kΩ, and 1 MΩ is shown in Figure 15.11. The system is specifically designed to measure differences among six nominally-equal, four-terminal standard resistors (RI,R2, ...R6)

A voltage (V) is applied across points A and A' of the hexagonal ring which divides the ring into two parallel branches each containing three resistors. Then, a DVM is used to measure voltages (VI, V2, ...V6) between opposing equipotential terminals of the resistors. Next, the applied voltage points across the ring are rotated in a clockwise direction to points B and B'. Again voltage measurements are taken between corresponding terminals of the resistors that are at nearly equal potentials. This measurement process is repeated a third time with voltage applied across points C and C'.

From the three subsets of measurements for the different connections of the applied voltage, a set of nine linear equations is formulated. Values of the unknown resistors can be calculated if the value of at least one of the resistors in the ring is known.

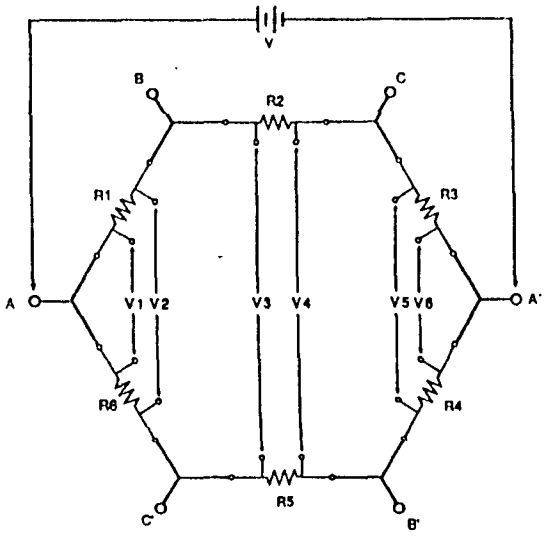


Figure 15.11-Unbalanced bridge circuit for six resistors

15.5.3 Resistance dividers

a) The Hamon Resistor

The Hamon resistor relies on a series-parallel equivalence of nominally equal resistances. Figure 15.12 shows the series-parallel equivalence of Hamon connected resistors.

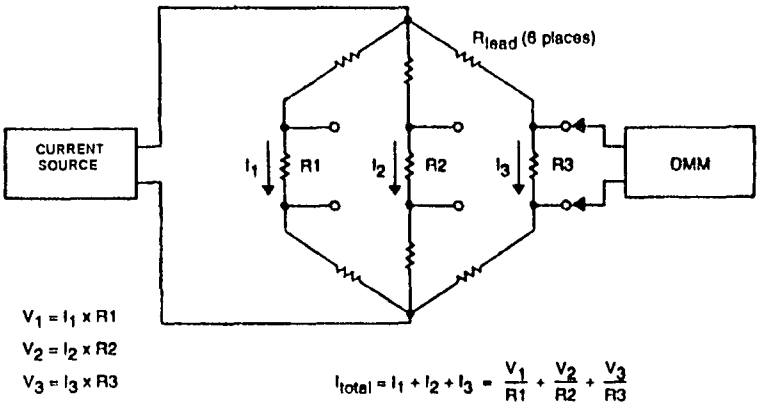


Figure 15.12 –Hamon connected resistors

The principal is illustrated using theree nominally equal resistors ,first connected in series and then in parallel. The average value of the three resistors is :

$$R_a = \frac{R_1 + R_2 + R_3}{3}$$

The series value R_s is given by:

$$R_s = R_1 + R_2 + R_3 = 3R_a$$

The parallel value of the three resistors is:

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$ which can be reduced to.

$$R_p = \frac{R_a}{3}$$

The ratio of Rs to Rp equals 9 for three resistors.In general if N nominally equal resistors are are placed in series and then in parallel, the ratio, R_s/R_p is given by :

$$\frac{R_s}{R_p} = N^2\left[1 + \left(\sum \varepsilon_i^2/N\right)\right]$$

where ε_i is the relative deviation of the i th resistance from the mean value of the N resistances.

This means that with a set of resistors matched to 1 part in 10^4,the ratio R_s/R_p is equal to N^2 within 1 part in 10^8, provided proper attention is paid to leakage resistances and connection resistances. However the design of such a series –parallel resistance device requires special precautions, described by Hamon (Ref).

Hamon resistance dividers are commercially available from several manufacturers,The ESI SR-1010 ,which has been used for may years in calibration laboratories and the more recently introduced Fluke 752A.

b) Kelvin-Varley divider

A Kelvin-Varley divider consists of several strings of resistors interconnected as shown in Figure 15.13 .

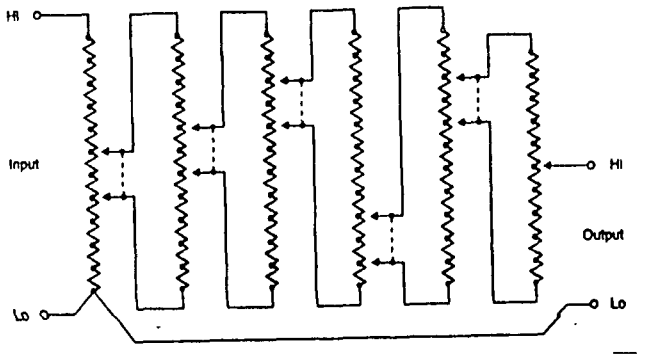


Figure 15.13-Kelvin-Varley divider

It can be used for generating reasonably accurate fixed ratios (±1 ppm of output at 10:1) the main application of a Kelvin- Varley divider is to finely subdivide a known input voltage. Although most of these strings consist of more than 10 resistors, they function as decades. Normally the first decade is composed of 11 equal resistors of a value R. To get an over-range capability of 10%, the first decade is constructed with 12 resistors. At any given setting of the first decade switch, two of these resistors are shunted by the second decade, which has an input resistance equal to the series value of the two resistors being shunted. Due to the combining effect of resistances in parallel, the voltage drop across the two shunted resistors is equal to the voltage across any unshunted first decade resistor. Stated another way, the end-to-end resistance of the decade, as shunted, is equal to the value of 11 resistors, rather than 12.

Two definite advantages are immediately evident: first, the input resistance measured from the input to the common terminal, with the output terminals disconnected or unloaded, is constant. Second, the effect of contact resistance in the switch points is greatly reduced because of the division of current. The second, third, and subsequent decades are also Kelvin-Varley elements. Each decade covers the range of one step of the preceding decade, in steps from one-tenth up to nine-tenths. The last decade consists of 10 equal resistors, and can be set to values of zero through 10. It is only by use of this 11 th setting of the last dial that the divider can be set to full scale. This dial's setting is equivalent to a setting of 10, displayed as an X, which is interpreted as 0, carry 1 to the next higher significant decade.

For example, a setting of 0.99999X would be interpreted as 1.0 because the carry of 1 from the X is propagated to the first decade setting.

If the basic scheme of the first two decades were to be continued for several subsequent decades, a major problem would arise. The total resistance of each decade (and therefore of the individual resistors) would have to decrease by a factor of five for each decade. This would soon lead to an impracticably small value of resistance. Therefore in commercially available dividers, the scheme is modified somewhat. Starting with the first decade, the entire decade is shunted by an additional resistor. The value of this resistor is adjusted to make the total shunt resistance seen by the previous decade have the proper value, and to allow the resistors in the string to have some minimum value, such as 1 kΩ. Such a divider produced by Fluke Mfg. is shown in Figure 15.14.

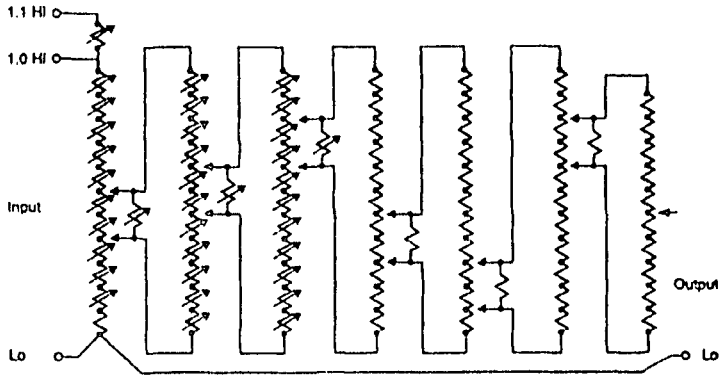


Figure 15.14-Modified Kelvin Varley divider manufactured by Fluke ,USA (Source :Fluke Mfg. Co. U.S.A)

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