WIKA-Handbook

**Pressure and
Temperature Measurement**
U.S. Edition

WIKA® CONNEXION

Printed in the United States of America

CONNEXION

Foreword

For more than fifty years WIKA has been a leading manufacturer of pressure and temperature measurement instruments.

Today, the name WIKA stands for a broad product range of industrial pressure and temperature measurement instrumentation.

The more than 300 million measuring instruments made by WIKA so far not only prove the quality of our products, but have also enabled us to gain an extensive knowledge of practical applications requiring the measurement of pressure and temperature.

The present new edition of the WIKA handbook is intended to provide a reference book for our worldwide customers, dealing not only with the fundamentals, but also important practical aspects of industrial pressure and temperature measurement.

Additionally, all new developments concerning mechanical and electronic pressure and temperature measurement are considered.

Alexander Wiegand

Introduction

Industrial development now faces challenges and opportunities of unprecedented magnitude and diversity. Economical manufacturing processes for existing or new products, new technology trends, the internationalization of markets and conditions of competition, new research developments and questions of safety for man and his environment call for innovative and visionary solutions. In many cases the optimum utilization of energy and raw materials, the reproducibility of product quality and the operational reliability of plants and equipment depend essentially on being able to control fundamental operations and parameters. Parameters of central importance in this respect are pressure and temperature. Their simple and exact measurement and control are becoming more and more important for many fields of technology and daily life. Indeed, they are already indispensable in heating, air conditioning, energy and vacuum systems, in chemical processing, petrochemicals, paper manufacturing, the food industry and biotechnology, and in automotive, mechanical, apparatus and plant engineering. The same appplies to measurement and testing laboratories and to the equipment needed to conduct experiments for research in the natural sciences and technology.

The success of measurement and control in the above mentioned fields depends greatly on the availability of useful measurement methods and test facilities.

The WIKA Handbook sets out to present all the measurement methods and equipment now in use in the technical field. In addition to reviewing the classical mechanical and electrical methods of measuring pressure and temperature, the book also takes a detailed look at modern electronic sensor principles. The measurement ranges of the instruments described extend from fractions of a millibar to 10^5 x atmospheric pressure, with greatly varying demands on precision. As for temperature measurements, the book describes methods for measuring the entire range from just above absolute zero to several thousand degrees Fahrenheit.

In addition to describing the actual measurement methods and equipment the reader will also find detailed information about the physical fundamentals of pressure and temperature metrology, measurement transducers, influencing variables and the demands placed on pressure and temperature instruments by process engineering. National and international standards and regulations are also covered extensively.

In its comprehensive treatment of all pressure and temperature measurement aspects this handbook is without equal. Details are presented in sufficient depth to grasp even complex subjects. Attention is drawn to specialized literature and relevant handbooks on physics and metrology where additional reading is required to answer further questions.

The WIKA Handbook will not only prove extremely useful for WIKA customers but will certainly also find its way into many measurement and testing laboratories.

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1 Pressure measurement

1.1 Pressure and its units of measurement

Pressure and temperature are among the most important physical variables. Pressure is defined as a force acting evenly over a given area.

$$\text{Pressure} = \frac{\text{Force}}{\text{Unit Area}} = \frac{F}{A} \qquad (1\text{-}1)$$

This force can be exerted by liquids, by gases or vapors, or by solid bodies. Surface compression takes place at the interface between two solid bodies, but for our purposes we can consider this additional force negligible.

The basic unit of force in the U.S. is the **Pound-force** (lb_f) which is the force exerted by one pound of mass.

If we take one square inch (in^2) as the basic unit of area, then we can define pressure as:

$$\text{Pressure} = \frac{lb_f}{in^2} = \text{lbs. per sq. inch (\textbf{PSI})} \quad (1\text{-}2)$$

Pressure can also be expressed in terms of metric (SI) units. The basic metric unit of force is the **Newton** (N) and the basic unit of pressure is the **Pascal** (Pa).

1.1.1 Common Units of Pressure

There are three general classifications for units of pressure measurement as follows:

Customary (inch, pound-force, second, ampere) - used primarily in English speaking countries, but in many countries are being replaced by SI units. *Customary units of pressure include PSI, in. Hg, in. H_2O, and oz/in².*

SI - Le Système International d'Unités - (meter, Newton, second, ampere) - Commonly used in Europe and now popularly known as "metric" units. *SI units of pressure include bar, mbar, Pa, kPa, MPa, and N/m².*

MKSA (meter, kilogram-force, second, ampere) - formerly known as "metric" units but are generally being replaced by SI units. *MKSA units of pressure include kg/cm², m H_2O, mm Hg, and torr.*

1.1.2 Pressure of gases

The molecules of a gas can be imagined as small spheres moving randomly in a closed container. As they move, they bounce off of each other and off of the container walls, which creates pressure.
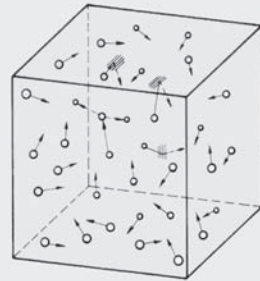
Figure 1.1   Molecular motion in gases

If **m** (lb) is the mass of a molecule of the gas, $\mathbf{v}_{med}$ (ft./s) the average molecular velocity and n the number of molecules contained in 1 ft³, then the pressure **p** is:

$$p = \frac{1}{3} \; n \cdot m \cdot v_{med}^2 \qquad (1\text{-}3)$$

Therefore the pressure of a gas depends on

- the number of gas molecules
- the mass of the gas molecules
- the average velocity of the gas molecules.

When a gas is heated, its average molecular velocity increases and the gas pressure rises.

This molecular mobility also explains the tendency of a gas to fill the entire volume of space available (referred to as **gas expansion**). It also means that a pressure exerted on a point of the container is equally distributed on all sides. The **distribution of pressure** takes place at the speed of sound.

Compared to solids and liquids, gases have a high level of compressibility. This relationship between volume **V** and pressure is described by Boyle's law:

$$V \cdot p = constant \qquad (1\text{-}4)$$

where the temperature is assumed to be constant.

Combining this law with Gay-Lussac's law leads to the **ideal gas law:**

$$\frac{p \cdot V}{T} = constant \qquad (1\text{-}5)$$

An important measurement, particularly for safety reasons, is the energy **W** of pressurized gases. At a volume $\mathbf{V}_0$ the energy of a gas at pressure $\mathbf{P}_e$ compared to the ambient atmospheric pressure $\mathbf{P}_{amb}$ is:

$$W_{gas} = P_e \cdot V_0 \cdot \ln \frac{P_e}{P_{amb}} \qquad (1\text{-}6)$$

1.1.3 Pressure of liquids

Unlike gases, liquids have a very low level of compressibility. For most applications, liquids can be assumed to be incompressible. Due to their elasticity, liquids revert back to their original volume when a pressure is removed.

When a liquid in a closed container is pressurized, its pressure is distributed equally to all sides just like gases. The distribution of pressure in liquids also takes place at the speed of sound.

Pressure in a liquid is called **hydrostatic pressure**. Since a liquid has a non-negligible mass, the force exerted by its weight generates a pressure that is independent of the shape of the container. It's pressure is determined by the height of the **liquid column** and its mass density ρ_m by the following relationship:

$$\Delta P = P_1 - P_2 = \Delta h \cdot \rho_m \cdot g \qquad (1\text{-}7)$$

where g = gravitational force

The **U-tube** manometer, the oldest pressure measuring instrument, was created based on this principle.
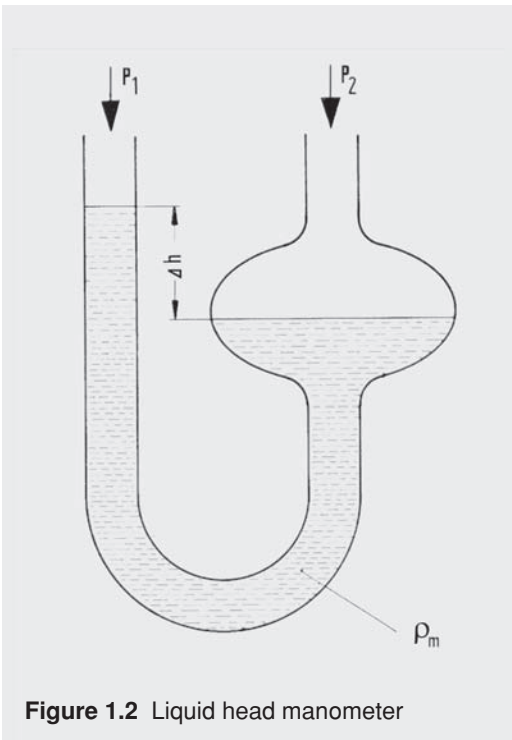
Figure 1.2 Liquid head manometer

The energy stored in a pressurized liquid is less than the energy of a pressurized gas by several orders of magnitude. If the liquid has a compressibility of χ, its stored energy is

$$W_{Liq} = \frac{1}{2} \; \chi \bullet V_O \bullet p_e^{\;2} \qquad (1\text{-}8)$$

A comparison of 1 in³ of water with an equal volume of gas at an overpressure of 15 PSI, shows the difference clearly:

$$\begin{aligned} W_{Liq} &= 1.5 \times 10^{-5} \; \text{in.-lbs} \\ W_{gas} &= 2.1 \times 10^{-1} \; \text{in.-lbs.} \end{aligned} \qquad (1\text{-}9)$$

1.2 Types of pressure

The different types of pressure differ only with respect to their reference point.

1.2.1 Absolute pressure

The most definite reference point is absolute zero pressure. This is the pressure of empty space in the universe. When a pressure is based on this reference point, it is called **absolute pressure**. To distinguish it from other types of pressures it is accompanied by the suffix "a" or "abs" (from the Latin: absolutus = independent, separate from).

1.2.2 Atmospheric pressure

The most important pressure for life on earth is atmospheric air pressure p_{amb} (amb = ambiens, surrounding). It is produced by the weight of the atmosphere surrounding the earth up to an altitude of about 300 miles. Atmospheric pressure decreases continuously up to this altitude until it practically equals zero (full vacuum). Atmospheric air pressure undergoes climatic changes, as shown by the daily weather report. At sea level, p_{amb} has an average value of 29.90 inches of Mercury ("Hg). In high or low pressure weather zones it can fluctuate by as much as ± 5%.

1.2.3 Differential pressure

The difference between two pressures P_1 and P_2 is referred to as the pressure differential $\Delta P = P_1 - P_2$. The difference between two independent pressures is called the **differential pressure**.
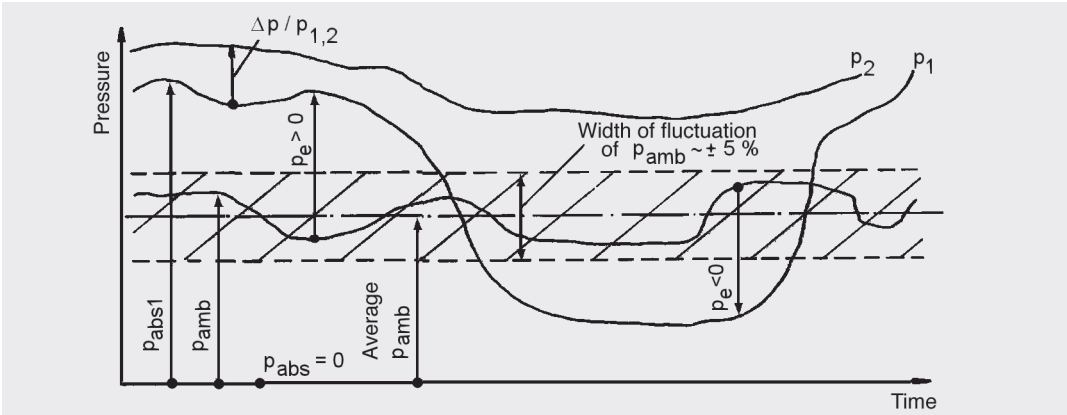
Figure 1.3 Types of pressure

1.2.4 Gauge Pressure and Vacuum

The most common measurement of pressure is **gauge pressure** (P_g) which is the pressure difference between the measured pressure and ambient pressure.

$$p_g = p_{meas.} - p_{amb} \qquad (1\text{-}10)$$

The term **pressure** is used if the measured pressure is higher than the atmospheric pressure.

The term **vacuum** is used if the measured pressure is below atmospheric pressure.

The use of either of these terms automatically implies that the pressure (or vacuum) being measured is with respect to ambient pressure (i.e. gauge pressure or vacuum). In order to distinguish absolute pressure measurements, the words "absolute pressure" must be used.

1.3 Common methods for measuring pressure

Accurately measureable pressures can vary from fractions of an inch of water (very low pressure) to over 100,000 PSI (extremely high pressure). The degrees of accuracy needed at these pressures also vary by application. To cover these variables, there are two basic types of pressure measurement; direct and indirect.

Direct-measuring pressure instruments determine the pressure from the basic equation:

$$p = \frac{F}{A} \quad \text{or} \quad \Delta p = \Delta h \cdot \rho_m \cdot g \qquad (1\text{-}11)$$

and get their readings from these relationships.

Indirect-measuring pressure instruments use the deflection of a flexible material or an electrical, optical or chemical effect to determine the measured pressure. Measuring converters are instruments which convert the pressure acting on them into an output which is generally an electric or pneumatic signal. This output is a function of the input pressure and can be either digital or analog.

1.3.1 Direct-measuring pressure instruments

1.3.1.1 Pressure measuring instruments using a liquid column (Liquid column manometers)

The measuring principle of a gauge using a liquid column, commonly referred to as a liquid column manometer, consists of comparing the pressure **p** being measured with the height **h** of a liquid column using the law

$$\Delta p = \Delta h \cdot \rho_m \cdot g \qquad (1\text{-}1)$$

The height of the **liquid column h** is read from a graduated scale. If higher precision is needed or if the measurement signal is to be processed further, the height difference is measured by a resistance wire inserted into the liquid or by the reflection of sound or light waves.

Selection of the liquid depends on the magnitude of the measured pressure. Commonly used liquids are alcohol, water and mercury. With a liquid column of 3 ft. as the practical height limit, the different densities of alcohol with $\rho_m \sim 0.5$ oz./in^3, water with $\rho_m \sim 0.6$ oz./in^3 and mercury with $\rho_m \sim 8.2$ oz./in^3 result in the following measurement pressures:

Alcohol	16.66 oz./in^2
Water	20.82 oz./in^2
Mercury	283.2 oz./in^2

These values show that a pressure measuring instrument with a liquid column is practical for the measurement of low pressures and vacuums or small pressure differences. Pressure difference measurements can also be made at high static pressures, as long as the tubes are designed to handle those static pressures.

Because of their reliability, liquid column manometers are fairly common.

The accuracy of measurements taken at room temperature with instruments based on the liquid column principle is approximately 0.3%, regardless of the point of measurement. For higher ac-curacy, significant corrective calculations are needed. Corrective calculations are also necessary if the temperature differs from the reference temperature. Factors such as temperature-dependent changes of the liquid's density, differences in the length of the scale and deviations of the factor of gravitational acceleration at the point of measurement must be taken into account. Contamination of the liquid also leads to density changes and a corresponding error in measurement. Furthermore, the influence of surface tension and its possible change due to external effects must also be taken into consideration, as well as the compressibility of the liquid.

The **surface tension of a liquid** is evident by its curved surface **(meniscus)** against the container walls. In small diameter tubes the entire surface will be curved. With liquids such as water or alcohol, which have a relatively low surface tension, the surface will be concave (Figure 1.4).
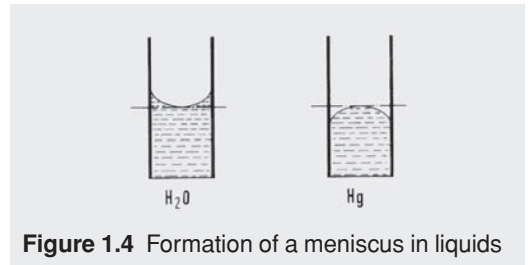
Figure 1.4 Formation of a meniscus in liquids

With mercury, which has a very high surface tension, the meniscus is convex. To avoid any ill effects of capillary elevation in small diameter tubes, liquid manometer tubes have a constant diameter. To avoid **parallax errors** when reading the pressure, the reading must be taken in the horizontal direction at the apex of the meniscus (Figure 1.5). Precision instruments have a mirror graduation or some other auxiliary device to ensure precise readings.
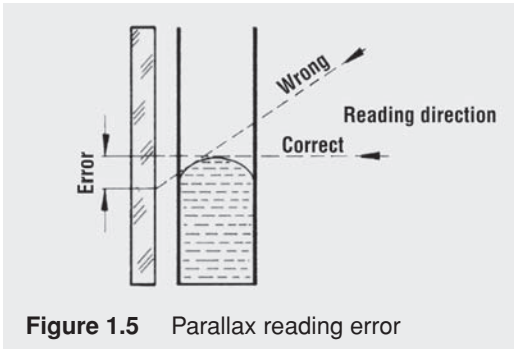
Figure 1.5   Parallax reading error

U-tube manometer

Liquid column manometers come in various configurations to meet specific requirements. The basic types are described below. The simplest liquid column manometer is the U-tube manometer.

U-tubes are built for pressures of between 4 "H_2O and 10,000 PSI. The maximum pressure differences Δp depend on the length of the tubes and on the density of the liquid.

Inclined-tube manometer

The **inclined-tube manometer** is used to measure very low pressures of up to about 4 "H_2O.

The sloping design of the tube stretches the graduation by an amount proportional to the angle of inclination α. For this reason, the angle of inclination of many inclined tube manometers can be adjusted. With unequal areas A_1 and A_2, the graduation will need to be corrected accordingly due to the changing level of liquid at A_1. For high precision, the measurement must be made very carefully. Generally these instruments are equipped with a bubble leveler for precise horizontal adjustment.

Figure 1.6   U-tube manometer
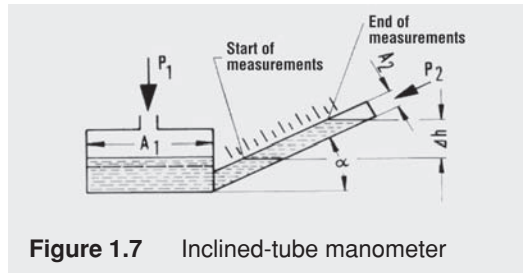
Figure 1.7   Inclined-tube manometer

When the pressures p_1 and p_2 are equal, the height difference Δh - and therefore Δp - is zero. With the same internal diameter, surface consistency and material, the capillary elevation has no effect.

Mulitple liquid manometer

A **mulitple liquid manometer** allows magnification of the measuring range by a factor of 8 to 10 because the measurement is based solely on the difference of the two densities.

$$\Delta p = \Delta h \, (\rho_{m2} - \rho_{m1}) \cdot g \qquad (1\text{-}13)$$

Figure 1.8 Mulitple liquid manometer
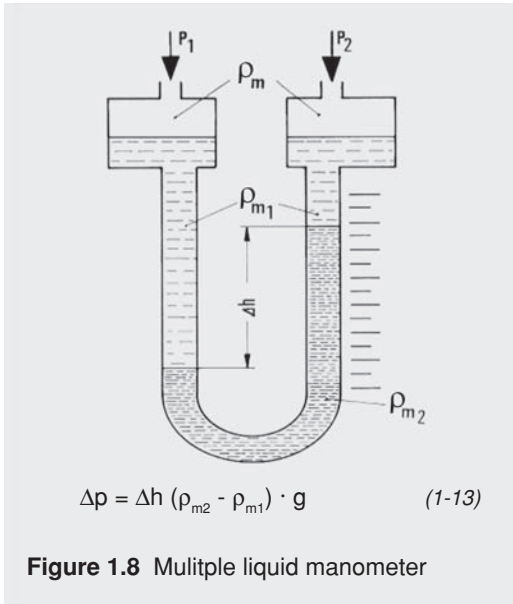
With multiple liquid manometers it is important that the separating liquids not mix with each other nor with the process fluid. If the process fluid density ρ_m and the separating liquid density ρ_{m1} differ, the change of height of the upper liquid level must be taken into account. This is particularly important for the measurement of gas pressures.

Float-type manometer

The float-type manometer tries to combine the advantages of easy reading on a graduated scale with the advantages of a liquid column.

Figure 1.9 Float-type manometer
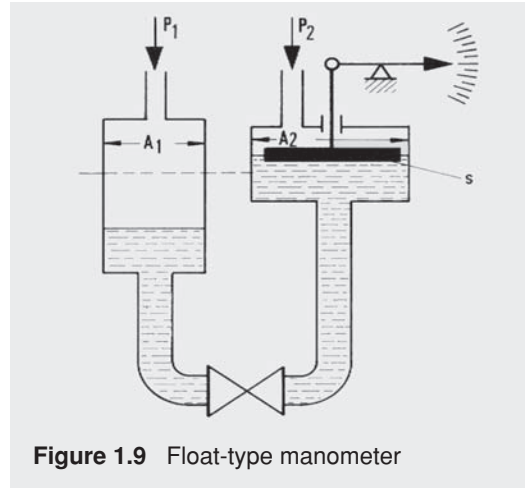
A float **S** follows the height of the liquid column and relays this height to the outside.

This design allows the instrument to be made of metal for operating pressures from 10"H$_2$O to 6000PSI. The measuring range can be changed by reversing the ratio A$_1$: A$_2$. The main problem with this type of instrument is that the friction occuring from the pressure-tight transmission of the measurement results adds error to the reading. Additional equipment can be added to the float-type manometer that determines the position of the float from the outside (i.e. ultrasonics) which then transmits the results to the graduated scale. However, even this additional equipment is not enough to maintain this instrument's former popularity.

1.3.1.2 Pressure balances with liquid separation

Pressure balances differ from the liquid column manometers described in Section 1.3.1.1 in that the separating liquid is used only to keep the pressure chambers apart. The pressure being

measured acts on a defined area A and is compared with a force due to weight G. Changes of density of the separating liquid do not affect the measurement.

The measuring principle of the pressure balance is best demonstrated by the **immersed bell**.

$$p = \frac{m \cdot g}{A} \quad (1\text{-}14)$$
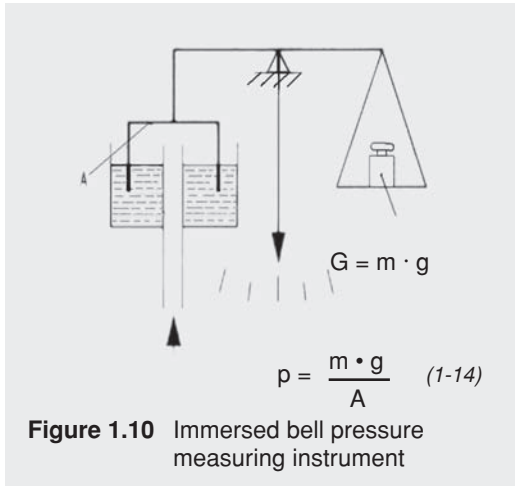
Figure 1.10 Immersed bell pressure measuring instrument

Replacing the reference weight G with a spring force results in a rotary movement that is proportional to the pressure and which can be displayed on a graduated scale for simple reading of the measurement.
The immersed bells shown here are used for the measurement of small pressures up to 0.5"H_2O with an accuracy of approximately 0.03%.
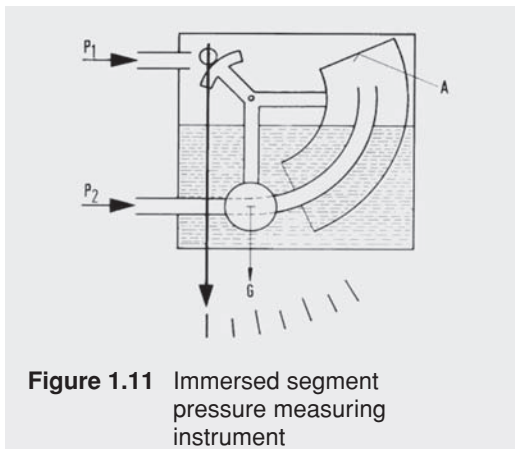
Figure 1.11 Immersed segment pressure measuring instrument
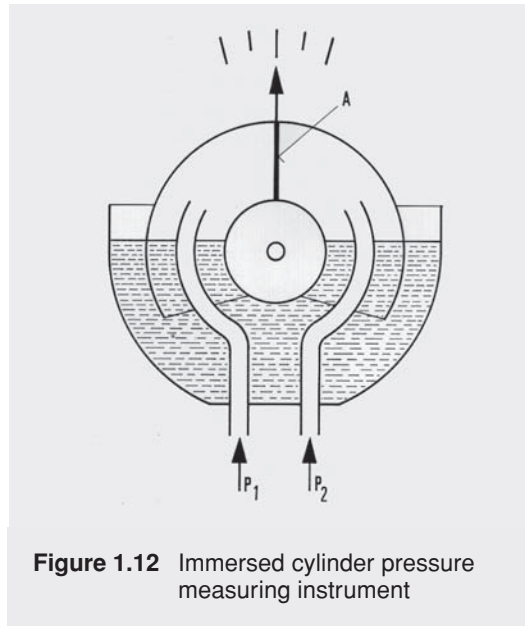
Figure 1.12 Immersed cylinder pressure measuring instrument
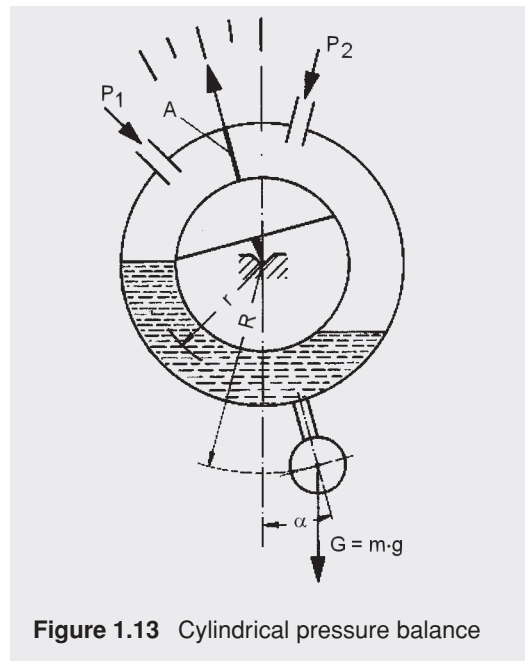
Figure 1.13 Cylindrical pressure balance

The **immersed segment** (Figure 1.11), the **immersed cylinder** (Figure 1.12) and the **cylindrical pressure balance** (Figure 1.13) use the same measuring principle at different operating pressures:

$$p = \frac{R}{r} \cdot \frac{G}{A} \cdot \sin \alpha \qquad (1\text{-}15)$$

They are mainly used for measuring small differential pressures with an accuracy of 0.5 to 1%. However, they are sensitive to pressure surges, require careful positioning and take up a great deal of space. The advantages of these instruments is their high adjusting force and therefore small measuring error, and their independence from liquid density and temperature changes. Still, the disadvantages outweigh the benefits and this type of instrument is therefore seldom used.

1.3.1.3 Piston-type pressure measuring instruments

Piston-type pressure measuring instruments function according to the basic definition of pressure

$$p = \frac{F}{A} \qquad (1\text{-}16)$$

The pressure acts on a known area A of a sealed piston, generating a force F. Simple piston-type pressure measuring instruments for industrial applications compare this force with the force of a spring. The spring travel is a function of the pressure that is read off of a graduated scale.

Piston-type pressure measuring instruments with a spring-loaded piston

Generally this type of instrument is very sturdy for high dynamic loads. Due to the friction between the seal and piston, they are mainly used for pressures of between 15PSI and 15,000PSI. Their dis-
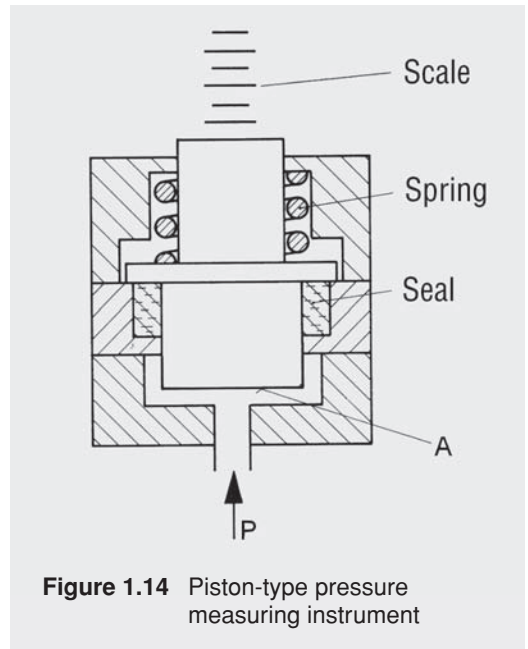
Figure 1.14 Piston-type pressure measuring instrument

advantages are seal wear and the difficulty of reading the indicated pressure on the short graduated scale. Their accuracy is generally between 1% and 5%. Limiting the piston travel gives excellent overpressure protection.

Dead-weight testers

Dead-weight testers have achieved considerable importance in calibration shops and laboratories where they are used as a pressure standard. The force of the piston is compared with the force of calibrated weights. Unlike the immersed bell instrument, the coupling does not take the form of a balance arm but instead uses a hydraulic liquid or gas as the pressure transfer medium.

$$P = \frac{m \cdot g}{A} \qquad (1\text{-}17)$$

Figure 1.15   Dead-weight tester with a simple piston

ancy with respect to atmospheric humidity and ambient air pressure, and the deformation of the piston and cylinder caused by the measured pressure. To compensate for these factors, there are different designs for the cylinder, piston and seal, all of them based on theoretical ideas. Besides the **simple-piston** instrument type shown in Figure 1.15, the **differential piston version** (Figure 1.16) has also gained considerable importance.

Dead-weight testers can measure pressures of up to 150,000PSI with accuracies of between 0.005% and 0.1%. Most applications are between 15PSI and 30,000PSI. The main problem with this type of measuring instrument is the sealing of the piston against the measuring chamber. Minimum friction is required in order to limit the measuring error, while leakage must also be kept to a minimum.

To meet these contradictory requirements, the right materials must be used for the piston and cylinder, and it is particulalry important to make sure the mating surfaces are of high-quality. The pistons, which are partly made of tungsten carbide, and the cylinders must fit together with a clearance of no more than several hundreths of an inch. The piston rotates while taking measurements in order to further minimize losses by sliding friction.

To be able to use dead-weight testers as calibration equipment at accuracy levels of 0.005 to 0.025%, it is necessary to take into account several factors that influence the readings. Such factors include local gravity, temperature, mass buoy-

$$p = \frac{m \cdot g}{A_1 - A_2} \qquad (1\text{-}18)$$

Figure 1.16   Differential piston

The differential piston design makes it possible to keep the active area as small as needed. This is important for the piston's stability at high pressures.

In the **deadweight-tester** with clearance compensation (Figure 1.17), that part of the cylinder wall used to guide the piston, is also subjected to the measurement pressure in order to minimize the effect of pressure changes due to piston clearance.
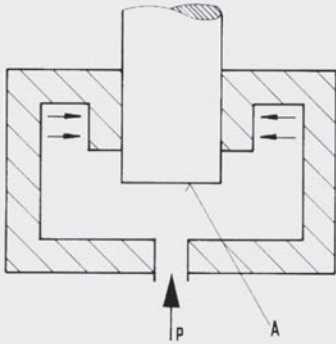
Figure 1.17 Piston with clearance compensation

This design can also be used in combination with the differential piston principle.
Deadweight testers are often used together with testing pumps.
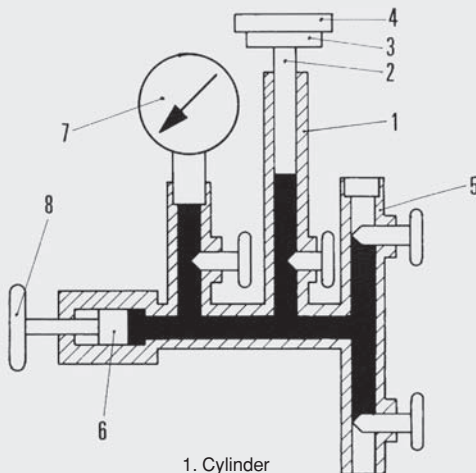
1. Cylinder
2. Piston
3. Weight support
4. Calibration weight
5. Filling connection
6. Testing pump
7. Instrument to be tested
8. Handwheel

Figure 1.18 Testing pump with deadweight piston

The testing pump is connected to the instrument being tested, to the actual measuring component (cylinder with a deadweight piston), and to the filling connection. A special hydraulic oil or gas such as compressed air or nitrogen is used as the pressure transfer medium.

After the filling connection is closed, the measuring piston is loaded with calibrated weights. The testing pump is started to generate a pressure until the loaded measuring piston rises and "rests freely" on the hydraulic fluid bed. The piston is rotated to reduce piston friction as much as possible.

Since the piston rests "freely" on the pressurized fluid bed, it exerts a pressure that can be calculated using the formula mentioned above. This pressure is the testing pressure for the gauge under inspection.

Deadweight testers should be calibrated on a regular schedule by a laboratory traceable to N.I.S.T. (National Institute of Standards and Technologies).

1.3.2 Indirect-measuring pressure measuring instruments

Indirect-measuring pressure measuring instruments use the effect of a pressure acting on materials or on bodies of a certain shape in order to determine the level of pressure. Examples of such an effect are the flexible deformation of hollow bodies or plates, the change of a material's electrical or magnetic characteristics, or optical and chemical effects on bodies and substances.

1.3.2.1 Pressure measuring instruments with flexible elements

Pressure measuring instruments with flexible elements are the most common pressure measuring devices used today. They combine a high grade of measuring technology, simple operation, ruggedness and flexibility, with the advantages of industrial and therefore cost-effective production.

Needing no external power supply, they are the best choice for most applications. The applications for pressure measuring instruments with a flexible measuring element range from highly automated chemical processes, i.e. in refineries or in plastics, pharmaceuticals and fertilizer production, to hydraulic and pneumatic installations in mechanical engineering, and even pressure cookers. These types of pressure measuring instruments can also be found at all the critical process monitoring and safety points of today's highly important energy installations - from exploration wells to power stations - as well as in environmental protection.

The principle behind these instruments is simple: the pressure to be measured is channeled into the chamber of a **measuring element** where one or more of its walls are flexed in a certain direction by an amount proportional to the pressure. The amount of the flexure is small, usually from just a few hundredths of a inch to a maximum of one-half inch. This flexure is then usually converted into a **rotational motion** by a **movement**. The pressure is then read off a graduated scale. A **case** protects the complete **measuring system** against external forces and damage.

In many applications the movement of the pointer is also used to show the measurement signal in analog or digital form with electric or pneumatic measuring outputs. Figure 1.19 shows the input to output flow chart for pressure measuring instruments with flexible elements.

Various accessories allow these instruments to fit into the process or to adapt them for special measurement problems, i.e. high temperature process fluids.

The case and its components are not only used to hold the measuring system in position but also serve to **protect the user** in the event of a leak in the gauge.

Because pressure measuring instruments with flexible elements are so widely used, they will be described separately in Section 1.4.
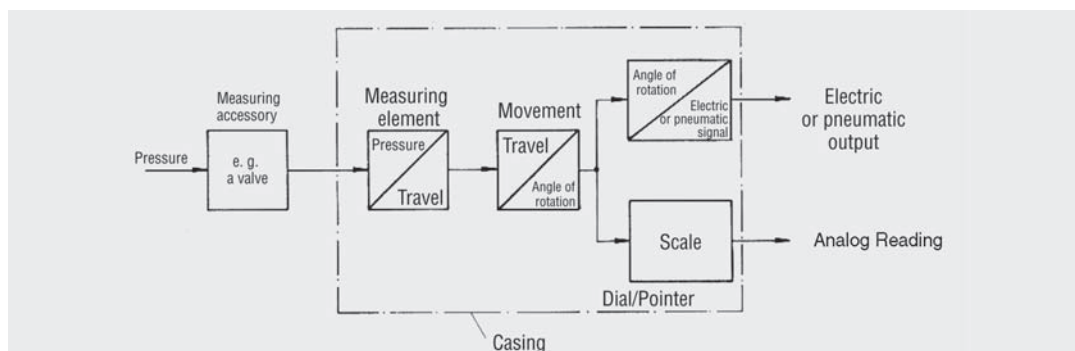
Figure 1.19 Flow chart of signal ouput, analog and digital, for instruments with flexible elements

1.3.2.2 Electrical pressure sensors and pressure measuring instruments

Today many measuring principles are used in electrical pressure measuring instruments. Most methods are based on the measurement of a displacement or force. In other words, the physical variable "pressure" has to be converted into an electrically quantifiable variable. Unlike mechanical pressure measuring methods, this conversion requires an external power source for the **pressure sensor**.

This pressure sensor is the basis of electrical pressure measuring systems. While mechanical gauge element displacements of between 0.004 and 0.012 inches are standard, the deformations in electrical pressure sensors amount to no more than a few microns.

Thanks to this minimal deformation, electrical pressure measuring instruments have excellent dynamic characteristics and low material strain resulting in high resistance to alternating loads and long-term durability. It is also possible to manufacture electrical pressure measuring instruments in very small overall sizes, i.e. by using semiconductor materials.

1 Pressure sensor element   2 Pressure sensing
3 Pressure transducer   4 Pressure measuring
                        instrument
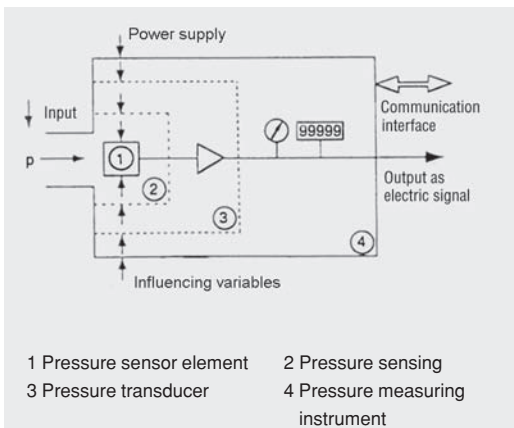
Figure 1.20 Basic design of all electrical pressure measuring instruments

Indicating and evaluating equipment such as measuring amplifiers, analog and digital displays, loggers, controllers, etc. are only described in this book where necessary for better understanding of sensor principles.

Sensor types with strain gauges

Semiconductor strain gauges (piezoresistive effect)

Semiconductor materials have been used for electrical pressure measuring purposes since the middle of the nineteen-sixties. Pressure sensors based on semiconductor materials (mainly silicon) are continuously being improved in parallel to developments in microelectronics.

The principle behind these instruments is described by the following equation, which defines the change of resistance in a tensioned wire.

$$\Delta R = \rho \cdot \Delta \left(\frac{l}{S} \right) + \Delta\rho \cdot \left(\frac{l}{S} \right) \qquad (1\text{-}19)$$

ρ = Specific electrical resistance
l = Length of the resistor wire
s = Cross-sectional area of the resistor wire

If this fixed-length wire is subjected to a force from all sides, its resistance changes as described.
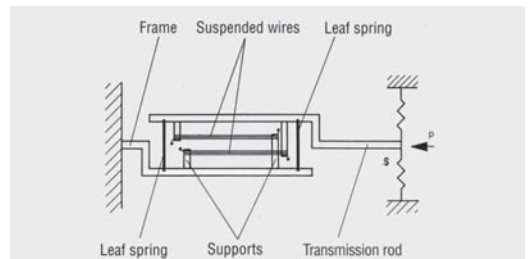
Figure 1.21 Pressure transmitter with freely suspended wires

The first part of the equation:

$$\rho \cdot \Delta \left(\frac{l}{S} \right) \qquad (1\text{-}20)$$

13

describes the change of electrical resistance caused by the change of conductor geometry. In the elastic range the elongation of the wire is accompanied by a corresponding reduction of its cross-sectional area. Close examination of the change of resistance in an electrical conductor makes this effect clearer:

$$R = \rho \cdot \frac{l}{S} \qquad (1\text{-}21)$$

If the length l increases, it is clear that there will be a reduction of the cross-sectional area, resulting in an increase of the resistance R.

The second part of the equation

$$\Delta \rho \cdot \left(\frac{l}{S} \right) \qquad (1\text{-}22)$$

describes the **piezoresistive effect**, which leads to a considerable change of resistance when subjected to mechanical loading. In semi-conductor materials this change of resistance is due to the changed mobility of electrons in the crystalline structure. With semiconductor materials (mostly silicon) the change of resistance is about 100 times greater than with metallic materials, allowing very small pressure sensors while still allowing very small measuring ranges into the "H_2O range on the other.

In the production of **silicon sensors** the base material is a specially grown silicon monocrystal. This monocrystal is then cut into **wafers**, paying attention to the orientation of the crystal structure because monocrystals display various properties in different directions (anisotropic).

The wafer is then polished. All the other processing steps, i.e. ion implantation, doping, etc., are common to the processing of silicon in electronics production and are not explained in this book.
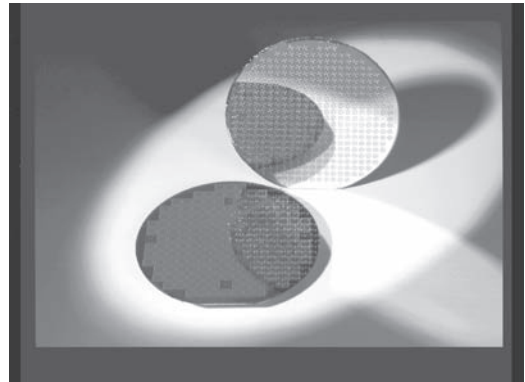
Figure 1.22 Wafers

Further key steps include the production of diaphragms by etching or boring. The resistors are attached (doped) into these diaphragms. Normally the resistors are attached on the edges of the diaphragm because this is where the greatest changes of stress - and therefore the biggest changes of resistance - occur when pressure is applied. Resistance changes equal to around 10% of the nominal resistance value occur under pressure.

This silicon wafer (also known as the system wafer) is then attached to a carrier wafer in an alloying process. This carrier wafer is made of the same material as the system wafer.

Finally, the carrier wafer is drilled with a hole for relative pressure measurements and then split into chips. The **silicon chip** is an elementary sensor with a very small overall size.
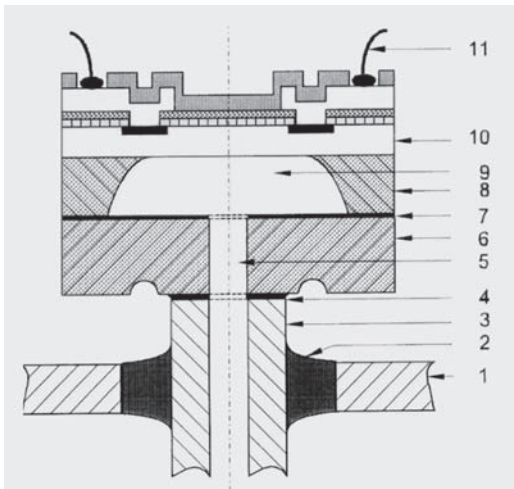
1. Base plate of the housing
2. Glass enclosure
3. Kovar[R] center tube
4. Gold-Tin solder
5. Relative pressure vent hole
6. Silicon carrier wafer
7. Metal alloy
8. Silicon system wafer
9. Cavity
10. Silicon epoxy layer (corresponds to a pressure-sensitive diaphragm)
11. Aluminum bond wires

Figure 1.23 Basic design of a pressure sensor

← 4 x 4 mm →   ← 1.5 x 1.5 mm →

Figure 1.24 View of a silicon chip

1. $R_1 = R_2 = R_3 = R_4$
2. $R_1, R_4 > R_2, R_3$
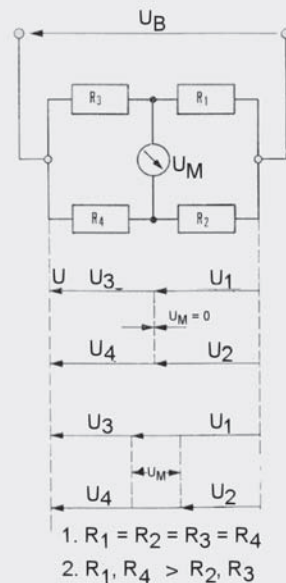
Figure 1.25 Basic design of a Wheatstone bridge circuit

To reduce the great temperature effects inherent with semiconductors, four resistors are joined together on the chip to form a **Wheatstone bridge**.

Figure 1.25 shows the basic design of a Wheatstone full bridge.

In practice the bridge is connected to more resistors for balancing, for temperature compensation and for setting the nominal sensitivity.

The bridge is said to be balanced when the output signal is U_M = zero. This is the case when the ratio of the resistors $R_1:R_3$ is the same as the ra-

tio of the resistors $R_2:R_4$, i.e. the drop in voltage over R_1 is the same as the drop in voltage over R_2.

As the result of the deformation caused by pressurization, the resistors R_1 and R_4 become bigger and R_2 and R_3 smaller (active full bridge). The measurement signal is therefore the bridge cross voltage U_{M3}, which can then be processed into a standard industrial signal in **the series-connected direct voltage amplifiers** or carrier frequency amplifiers.

Resistive sensors are the most widespread sensors in industrial use.

$$U_S = U_B \cdot \frac{R_1(p) \cdot R_4(p) - R_2 \cdot (p) \cdot R_3(p)}{[R_1(p) + R_3(p)] \cdot [R_2(p) + R_4(p)]} + U_0$$

(1-23)

U_s = Signal voltage
U_B = Supply voltage
U_0 = Offset voltage
$R(p)$ = Pressure-dependent resistors

Metallic strain gauge

The principle of the metallic strain gauge was discovered in 1843 by the physicist Wheatstone. Since then it has been used in various applications, including electrical pressure measurement. Pressure sensors with metallic strain gauges generally differ in the way they are applied to the deformable bodies. All these strain gauges are governed by the following equation:

$$\frac{\Delta R}{R} = k \cdot \frac{F}{A \cdot E}$$

(1-24)

$R, \Delta R$ = Resistance, change of resistance
K = Constant proportionality factor
E = Modulus of elasticity of the spring material
F = Mechanical force (in our case $F = p \cdot a$ proportional to the pressure)
A = Pressurized area

From this equation it is clear that the measured variable P and the change of resistance (ΔR) are linearly proporational.

Strain foil gauges

For a long time, **strain foil gauges** were the most popular sensors for pressure measurement. Their main advantage is that they can be easily applied to any deformable body using adhesive materials.

The strain foil gauge usually consists of a carrier foil typically made of phenolic resin and measures between 0.2 and 0.6 thousandths of an inch (5 and 15 mm) thick. Since this foil is nearly always applied to metallic base materials, it also acts as an insulator. This carrier foil holds the metallic strain gauge, which consists of an approximately 0.2 thousandths (5 mm) thin winding-shaped measuring grid. The strain gauge material is usually Constantan.
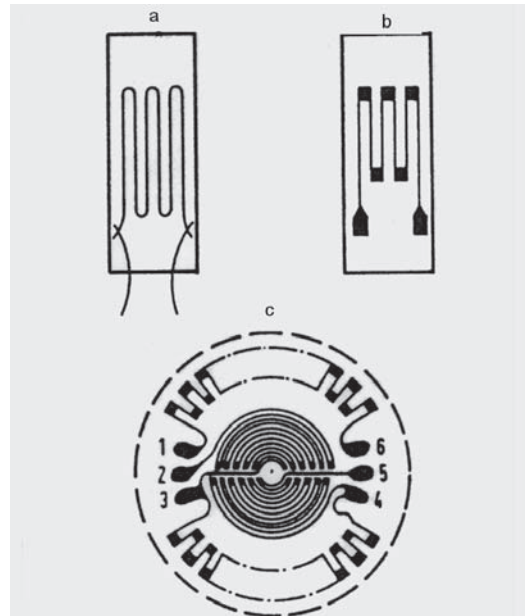
Figure 1.26 Different designs of strain foil gauge
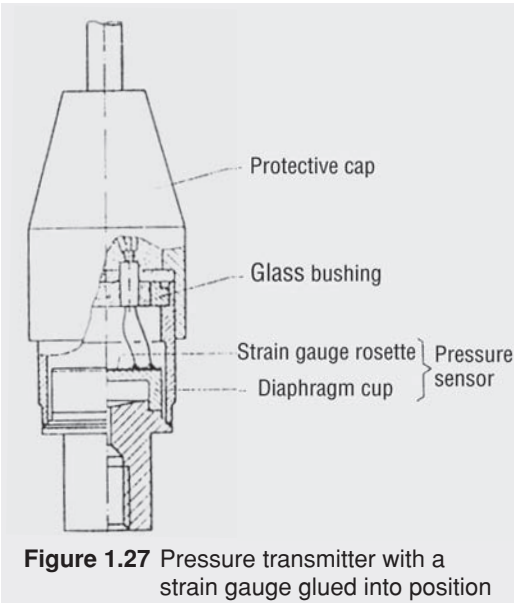
Figure 1.27 Pressure transmitter with a strain gauge glued into position
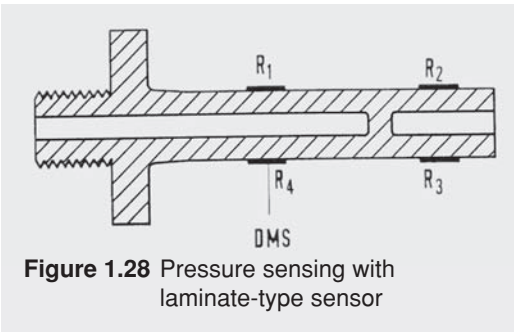
Figure 1.28 Pressure sensing with laminate-type sensor

To protect the thin strain gauge layer, an additional plastic film is applied over the strain gauge. Strain foil gauges are relatively easy to use and they can also be applied to curved surfaces (see Figure 1.28). They are still a popular choice, therefore, especially for the simple measurement of forces.

One of their big drawbacks, however, is the actual bonding, because this necessitates applying an additional inorganic binding agent between the deformable body and the strain gauges. Differences between the coefficients of expansion of the materials used result in unequal elongation when the temperature changes, and this leads to a corruption of the output signal. These effects can only be minimized with elaborate compensation measures.

Furthermore, the strain foil gauge tends to creep under load due to the elasticity of the necessary bonding material. Modern strain gauge production techniques and specially formulated adhesives help to compensate for these negative factors but cannot eliminate them completely.

Thick-film strain gauges

Thick-film technology has been successfully used for several years in the production of electronic circuits. It represents a cross between an integrated circuit and an SMD chip (SMD = surface mounted device). The thick-film circuit (also called a hybrid circuit) is applied to a carrier material, which is usually made of an aluminium oxide ceramic (Al_2O_3) or a stainless steel diaphragm. Thick-film technology allows resistors, insulating layers, conductors, and to a limited extent, even capacitors to be manufactured in an additive printing process.
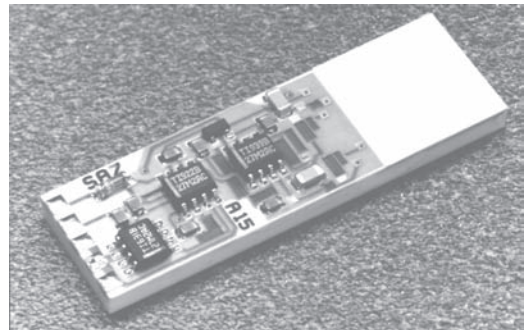
Figure 1.29 Hybrids for sensor applications

Different paste materials exist for the various levels of resistance. Strain gauges can be printed with these pastes on a substrate (carrier material). These resistors are then baked onto the substrate in an oven at process temperatures of between around 1550°F and 1750°F (850°C and 950°C).

Substrate materials such as Al_2O_3, which are also used as a diaphragm material for capacitive pressure sensors, have very good elastic properties and are virtually free of hysteresis. Another advantage of this technology is that it allows the possibility of installing the complete compensation and evaluation electronics on a substrate by the SMD method in a single operation.
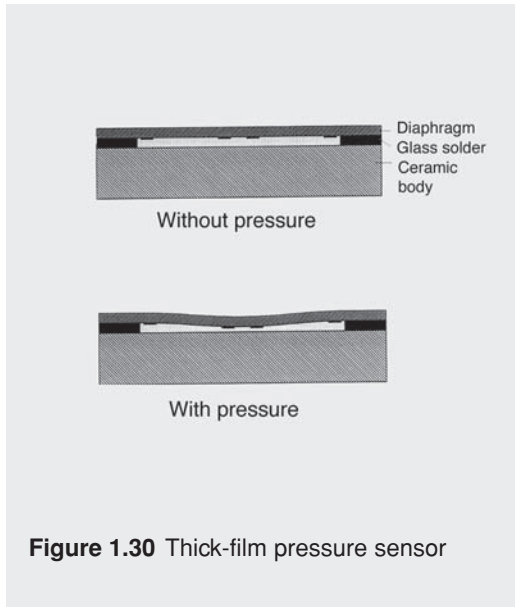
Figure 1.30 Thick-film pressure sensor

Figure 1.30 shows that the diaphragm with the printed resistors is joined to the ceramic carrier using a glass solder. As with all deformable diaphragm bodies, the force-related measuring range can be varied by altering the diaphragm thickness or size.

For many industrial pressure measuring applications, ceramic is usually not compatible with process media. It is possible, however, to apply the strain gauge to stainless steel diaphragms. These metallic diaphragms require an additional insulating layer between the resistors and the diaphragm. When choosing the materials for the metallic diaphragm it is important to select steels which have only slight scaling at the high process temperatures of up to 1750°F (950°C).

Very high production capacities have been developed over the past few years for this technology. Therefore, for applications requiring large numbers of gauges, thick-film technology is an economical alternative to the strain foil gauge.

Thin-film strain gauges

The most modern strain gauge production process is based on thin-film technology. It combines all the advantages of the conventional strain foil gauge without any of its disadvantages. The main advantages are very low temperature sensitivity and excellent long-term stability.

In most cases the deformable body is a diaphragm with a simple circular shape.
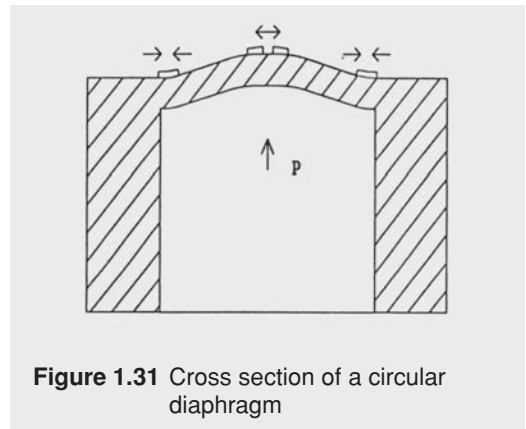
Figure 1.31 Cross section of a circular diaphragm
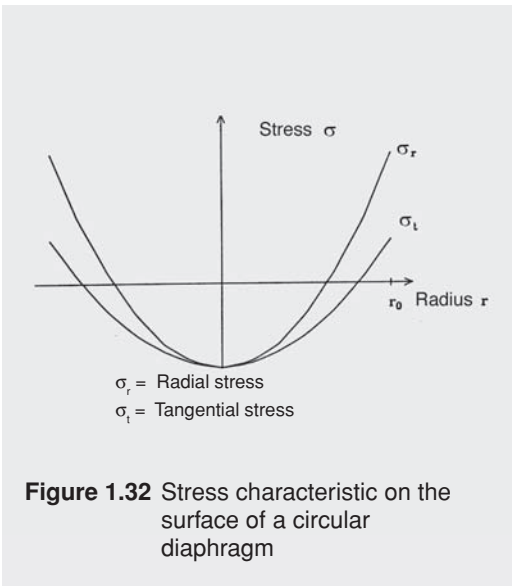
Figure 1.32 Stress characteristic on the surface of a circular diaphragm

k values of various materials:

Material	k value	Application
NiCr	approx. 2	Metallic strain gauge
Si	approx. 100	Semiconductor strain gauge
Ruthenium oxide	approx. 15-20	Thick-film strain gauge

On thin-film strain gauges, four resistors are again connected together to form a Wheatstone bridge. The resistors are positioned in those areas of the diaphragm where the greatest changes of stress occur. When pressure is applied, the resistors experience the greatest elongation at the center of the diaphragm and the greatest compression along the edges. This results in the following equation:

$$U_S = U_B \cdot \left(\frac{\Delta\rho}{\rho} + k \cdot \varepsilon \right) \qquad (1\text{-}25)$$

U_B = Voltage supply
U_S = Signal voltage
ρ = Specific resistance of the bridge resistors Ri
$\Delta\rho$ = Change of ρ with the elongation
ε = Elongation
k = k factor

These strain gauges are made of exotic materials, i.e. NiCr and semiconductor materials such as silicon. The main differences lie in their k values.

In the next section we will take a detailed look at the technology and production of pressure sensors with metallic strain gauges. The base materials for the diaphragms consist of metals which have a low deformation hysteresis. CrNi steels are normally used in order to achieve a high degree of compatibility with the process media. Special materials such as Elgeloy or Hastelloy C4 are also used but only in specific applications due to their difficulty to process.

As for the diaphragm shape, a distinction is drawn between circular and **annular diaphragms**. The advantage of an annular diaphragm is that there is no **balloon effect** (additional elongation) acting on all four resistors and resulting in a linearity deviation.
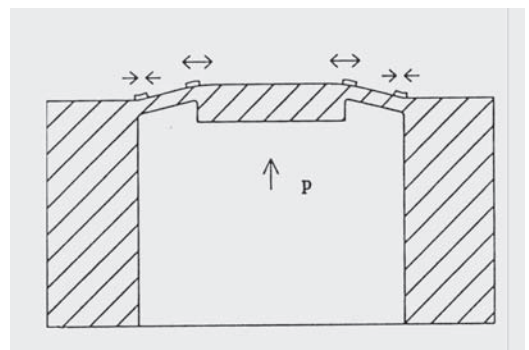
Figure 1.33 Cross section of an annular diaphragm

On an annular diaphragm, the strain gauges are positioned over the inner and outer bending edge, as shown in Figure 1.33. This is where the diaphragm experiences the greatest changes of stress.

The production of thin-film pressure sensors is a combination of the high-precision mechanical fabrication of a deformable body and the covering of this body with strain gauges in a variety of processes.

First, the thickness of the diaphragm must be kept to very close tolerances, mainly by lapping. The surface of the diaphragm is then prepared for the actual coating process by polishing to a maximum peak-to-valley height of approx. 0.1 μm. The next step is to apply an **insulating layer** to the polished stainless steel membrane. This can be accomplished, for example, by the **PECVD process** (plasma enhanced chemical vapor deposition).

In this process a coat of SiO_2 is applied to the diaphragm surface. SiO_2 is similar to glass in its insulating properties. This layer is around 4 to 6 microns thick and has an insulating resistance of at least 2 mega-ohms.

The actual resistance layer is then applied by a **sputtering process** (cathode ray sputtering).

After the resistance layer has been applied in a thickness of 50 to 200 nm, the actual strain gauges are produced using photolithography in a wet etching process.

Figure 1.35 Sensor with thin-film strain gauges
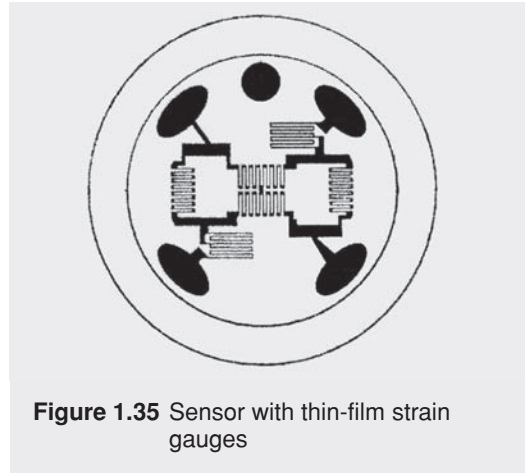
Further insulating, passivation and contacting layers are added, as in thin-film technology. It is possible to include temperature compensating resistors in the sensor layout in addition to the strain gauges.

Diode sputtering   High-performance sputtering

Figure 1.34 Sputtering process

This process is a controlled glow discharge and is performed under ultra high vacuum. The diaphragm material and the insulating layer form a molecular bond which is required for a break-free compound that guarantees very good long-term stability.

Figure 1.36 7 mm thin-film sensor element

Thin-film sensors are becoming increasingly important, particularly for high-pressure measurement.

Strain gauge transmission principles

As mentioned in the previous section, the many types of strain gauges are used for electrical pressure measurement. Strain gauges themselves only convert a deformation (elongation or compression) into a change of resistance, so they must be applied to a deformable body. From the equation for pressure:

$$p = \frac{F}{A} \qquad (1\text{-}26)$$

it is clear that a specific defined area A is required for the creation of a deformation in order to determine the force via pressure. Materials with very good elastic properties are used for these deformable bodies. Stainless steels are used as a rule because of their elastic properties and good compatibility with process media. Ceramic materials are also being used more and more often due to their good diaphragm properties. It is a characteristic of these materials to produce a strictly linear elongation (conforming with Hooke's law) on their surface when pressure is applied. This effect is used in the following conversion principles.

Diaphragm conversion

In most cases of diaphragm-based conversion, circular diaphragms or annular diaphragms are used. These diaphragms can be calculated and manufactured relatively easily.

The stress characteristic in a circular diaphragm is shown in Figure 1.32. The strain gauge is applied to the side facing away from the medium. One advantage of these diaphragms is that the measuring range can be adjusted by changing the diaphragm diameter or the diaphragm thickness. When selecting the diameter and the thickness, it is normal to choose a diaphragm that has a maximum elongation of around 1.1 to 1.3 inches/foot (900 to 1100 mm/m). This equals an elongation of around 0.1%.

The pressure ranges in which these circular and annular diaphragms are used are between around 15 PSI and approximately 60,000 PSI (1 to 4000 bar).

A different type of diaphragm-based conversion is applied in piezoresistive sensors based on semiconductor materials. Since the diaphragm material (silicon) and electrical connection of the actual pressure sensor are very sensitive and incompatible with most media, the pressure must be directed onto the silicon diaphragm using a separating diaphragm and a pressure transfer liquid. Silicone oil is mainly used as pressure transfer medium. Convoluted diaphragms made of stainless steel are then used on the side facing the medium.
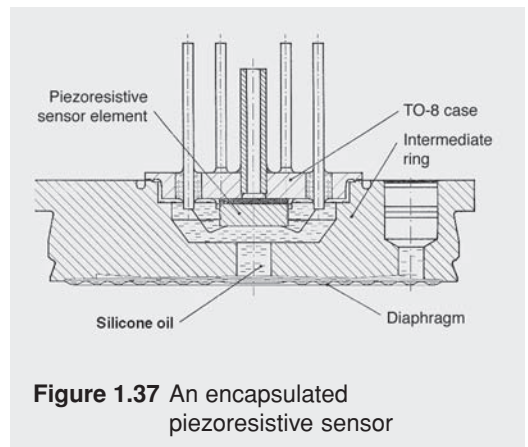
Figure 1.37 An encapsulated piezoresistive sensor

Bending beam conversion

Conversion methods based on the bending beam principle have proven successful particularly for thin-film strain gauges. With this principle the pressure is usually detected using a shaft-mounted diaphragm and transferred to a fixed bending beam with a linking rod acting via a mechanical transmission. The input of force causes the **bending beam** to deform in an S-shape. The strain gauges are applied to those areas with the greatest compression or elongation and are combined to form a Wheatstone bridge.
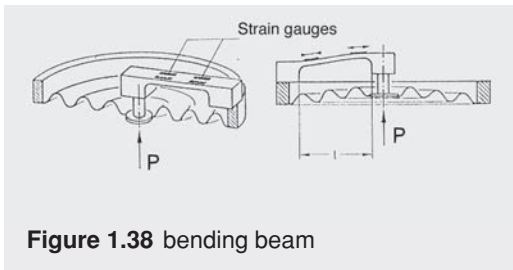
Figure 1.38 bending beam

The main advantage of these bending beams is their low-cost production, because the costs of thin-film processes rise in proportion to the surface areas involved, and the bending beams have very small dimensions.

This conversion principle is used in the pressure ranges between 10PSI and approximately 10,000PSI (0.6 bar to 600 bar).

Sensor principles with displacement measurement

Sensor principles based on the measurement of a displacement differ from sensors with a strain gauge, although in both cases the pressure is converted via a diaphragm into a force which then produces a measurable deflection.

Hall effect sensors

A **Hall effect sensor** is a magnetic field sensor which measures the deflection of a diaphragm or Bourdon tube for pressure measurement purposes. This change of position or change of magnetic field is converted into an output signal proportional to the pressure. With this system it is therefore possible, for example, to measure the travel of a Bourdon tube and to have an analog indicator (i.e. a pointer) to show the measured value visually at the same time.
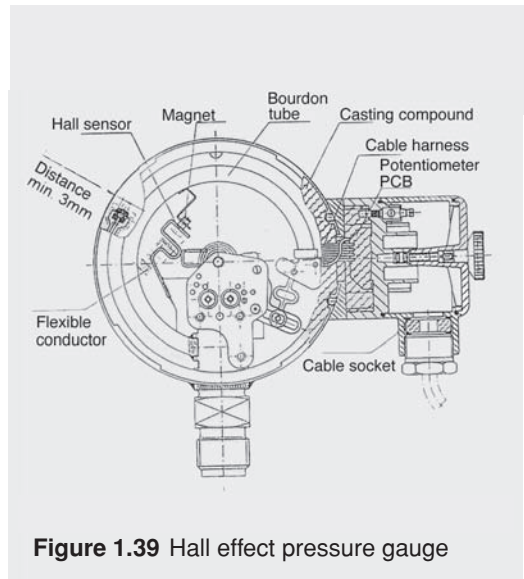
Figure 1.39 Hall effect pressure gauge

Today, this measuring principle is used in applications where flexible elements have proved successful. In addition to their built-in indicators these instruments also produce an analog output signal without having to install a second measuring instrument.

Capacitive sensors

The capacitance of an electrical capacitor is defined by:

$$C = \varepsilon_0 \cdot \varepsilon_R \cdot \frac{A}{l} \qquad (1\text{-}27)$$

$$\text{where } \varepsilon_0 = \frac{1}{36} \cdot 10^{-11} \cdot \frac{F}{cm}$$

($\varepsilon_0 = $ Dielectric constant of empty space)

If we assume that the value for ε_R and the size of the active area remain practically constant, the capacitance of a capacitor can be determined from the distance between the capacitor surfaces. This indirect measurement of the distance between the capacitor plates is used in the capacitive pressure sensors now in common use.

Part of the face of a circular diaphragm, for example, is used as one of the capacitor plates, while the second capacitor surface is formed by the fixed, immobile base plate.
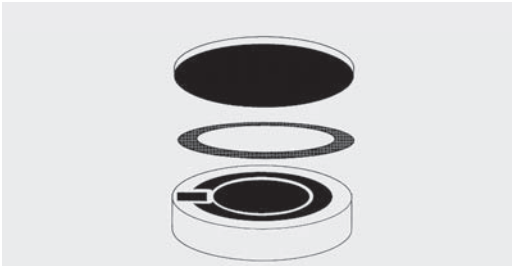
Figure 1.40 Structure of a capacitive sensor
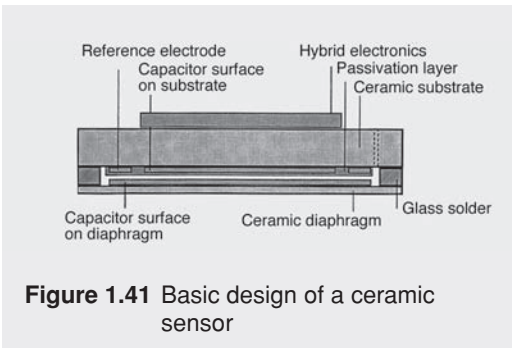
Figure 1.41 Basic design of a ceramic sensor

In Figure 1.41, the electrodes shown on the base body of a ceramic sensor and the grounding electrode on the diaphragm together form the capacitances C_P and C_R. The measuring capacitance C_P is located at the center of the diaphragm where the greatest deflection occurs when pressure is applied.

The **reference capacitance** (C_R) is located accordingly along the edge of the diaphragm. The reference electrode is positioned in the outermost area of the diaphragm because here (as close as possible to the diaphragm fixture) there is no change in distance between the electrodes. This reference capacitance is used to establish the **dielectric constants** for determining the current

measured value. The relationship between pressure and capacitance is then as follows:

$$p = (C_p - C_R) / C_p \qquad (1\text{-}28)$$

By using Al_2O_3 as the material for the diaphragm, its deflection is virtually linear. The insignificant mathematical nonlinearity of approximately 1% is very easy to compensate.

To obtain a signal, the capacitor is connected as part of an **oscillating circuit** that is powered with high-frequency alternating voltage and whose natural frequency varies with the magnitude of the capacitance. Due to of the high-frequency supply voltage and its associated interference from cable capacitances, moisture, etc., capacitive pressure sensors are nearly always used with an integrated signal conditioner, mostly using an ASIC (ASIC = application specific integrated circuit).

The distance between the electrodes equals approximately 0.004 inches (0.1 mm). The maximum diaphragm deflection is approximately 1 inch (25 mm). One of the great advantages of capacitive pressure sensors is their ability to withstand high overloads due to the diaphragm being in contact with the sensor body. Small measuring ranges, for example, can withstand up to 100X overloads.

The diaphragms are soldered to the solid base at a temperature of around 900°F (500°C) using a solder ring. The thickness of the particular diaphragm depends on the specific pressure range.

Capacitive **ceramic measuring cells** have an approximately 10X higher sensor signal than piezoresistive sensors. This high signal is used in transmitters to expand the measuring span. They are also suitable for extremely low pressures starting from 1"H_2O (2.5 mbar).

Inductive sensors

The inductive sensor systems commonly used today work mainly with **differential transformers** or with setups in which the change of magnetic resistance is measured.

The similarity with these systems is that they must change the position of the soft iron core or damping plate by around 0.02 to 0.04 inches (0.5 to 1 mm) in order to influence the magnetic flow between the primary and secondary coils. This is accomplished using diaphragm springs or Bourdon tubes.

Because of their relatively large displacement and the mass of the soft iron core or damping plate, inductive pressure sensors are used only for measuring static pressures.

Figure 1.42 Schematic of an LVDT sensor
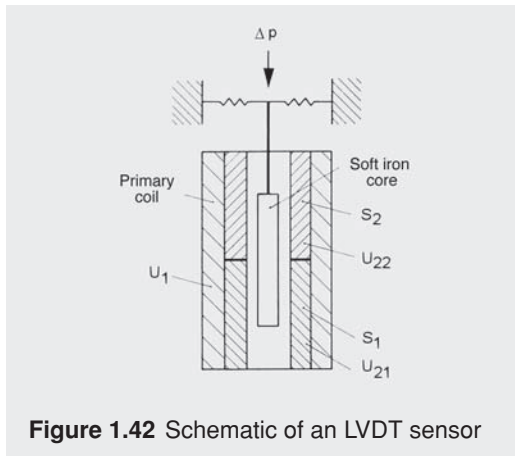
Figure 1.42 shows the setup of an LVDT sensor (LVDT = linear variable differential transformer). The primary coil is supplied with alternating voltage U_1. This alternating voltage is transmitted to the secondary coils S_1 and S_2. The magnitude of the induced voltage is conditional on the position

$$U_2 = U_{21} - U_{22} = k \cdot s\,(p) \cdot U_1 \qquad (1\text{-}29)$$

of the magnet core or plate and the resulting transformer coupling. The required output signal is produced by rectifying and amplifying the voltage.

Figure 1.43 Schematic of an LVR sensor
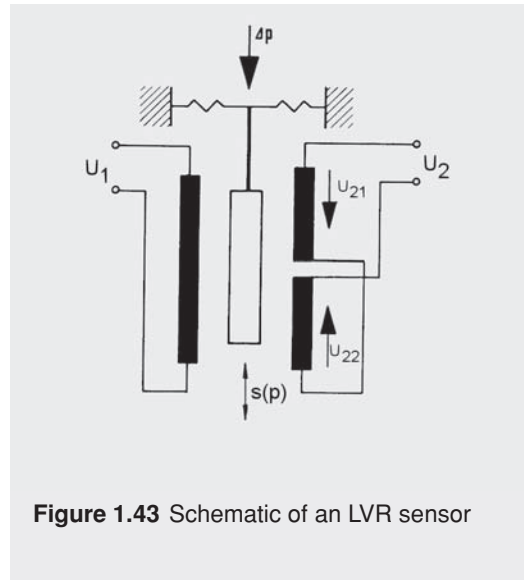
Slot initiators are a special design of LVR sensor (LVR = linear variable reluctance) in which the change of magnetic damping is affected by varying the depth of immersion of a metallic flag attached to an flexible measuring element in the slot of the initiator.

Pressure measuring instruments with slot initiators are rarely used today because equally good results can be achieved using sensor principles requiring far less effort.

Potentiometric sensors

The potentiometric pressure sensor is a type of **resistive sensor** which, once widely used, is rarely used any longer for demanding measurement jobs due to its short life span. This is due to the high loading of the resistor elements. The latter are in continuous mechanical contact with the slider, which is designed as a voltage divider. Fur-

thermore a relatively large displacement of the flexible measuring element is required for the deflection of the slider, a fact that greatly restricts the sensor's use for dynamic pressure characteristics. The continuous contact between the slider and the resistor track also creates friction, leading to less responsiveness and to hysteresis (not an isolated sensor system).

The main advantage of potentiometric sensors is their easy adaptability, i.e. to pointer-type instruments in which the slider of the potentiometer is connected with the pointer shaft. This means that the resistance value (and hence the sensing voltage) is changed directly between the start of the conductor and the slider.

Other sensor principles

Many other types of instruments exist for measuring low and high pressures in addition to those based on electrical pressure measuring systems presented above. They include:
- McLeod **compression gauges**
- **Pirani vacuum gauges** based on the principle of thermal conductance
- **Ionization pressure gauges**
- **Friction pressure gauges** which use the internal friction of gases as the basis for pressure measurements

These systems have gained little importance, however, in industrial pressure measurement.

Piezoelectric effect

The **piezoelectric effect** was discovered in 1880 by Pierre Curie. He found that an electric charge formed on the surface of certain materials when they were mechanically loaded. This charge is proportional to the acting force and can therefore be used for pressure measurement purposes. These materials require no external power to convert the physical measured variable.
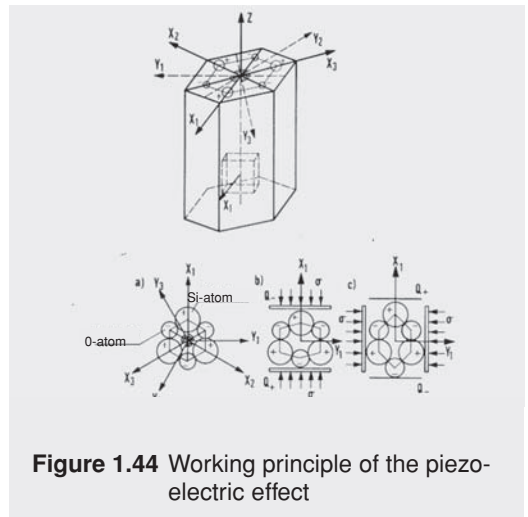
Figure 1.44 Working principle of the piezo-electric effect

In piezoelectric sensors, a diaphragm is used to convert pressure into a mechanical force. This mechanical force is then transmitted via piezoresistive rods using the transversal effect, i.e. the charge forms on the non-loaded surfaces. Crystals such as tourmaline and quartz, or ceramics such as lead zirconate and lead zirconium titanate can be used as sensor materials.

Piezoelectric sensors are useful mainly for the measurement of dynamic pressures, because with slow pressure changes or with static pressures the charges discharge through the finite insulation resistors. Amplifiers with very high input resistances are needed for the signal conditioning.

Signal flow of a piezoelectric pressure measuring system

Figure 1.45 A piezoelectric pressure sensor
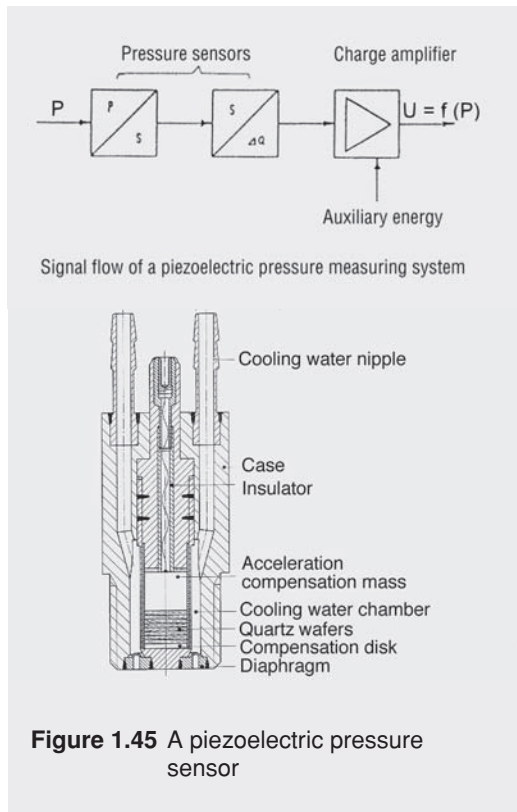
Piezoelectric sensors have become popular particularly in **engine monitoring systems**, for optimization of engine combustion processes. In this application they are highly rated for such sensor-specific properties as dynamic response, high resolution with accuracies of 0.1% of the measuring span, and a high operating temperature range.

Sensor principles for inspection and calibration systems

Unlike pressure sensors for industrial duty, where ruggedness and ease of operation are important, the crucial criterion for sensors used in inspection and calibration is a high-precision signal. For this reason the analog-digital pressure sensors are

widely used for this application. A number of these sensors are described below.

Quartz helix sensor

Quartz helix sensors are based on the **force-compensation principle**, i.e. the pressure is directed onto a helix made of a specially treated quartz glass.

Figure 1.46 Quartz helix sensor
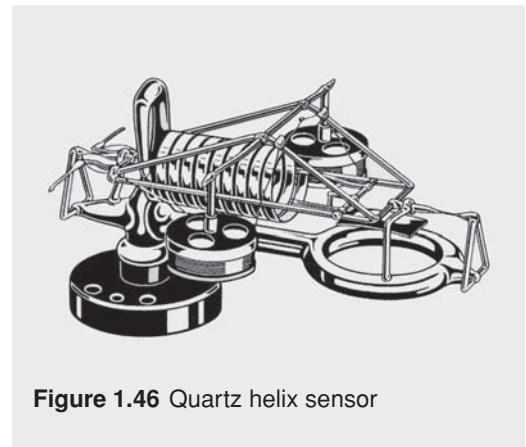
In the unloaded state (zero pressure), a beam of light produced by a light source is reflected from a convex mirror to a defined point in a photocell arrangement. When pressure is applied to the helix, the latter tries to rotate, causing the convex mirror to leave its zero position.

The diversion of the light beam produces a positive or negative voltage in the photocells, depending on the direction of rotation. This voltage is directed to a servo amplifier and from there to two solenoids, which are attached to the arms on the sensor as part of the servo system.

Figure 1.47 Quartz helix system
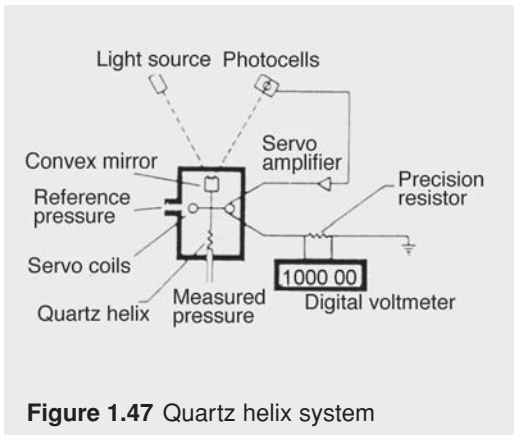
The servo coils are positioned inside a magnetic field produced by permanent magnets. The flowing current generates a force in these servo coils that counteracts the rotary force of the pressure. The strength of the current is increased until the beam of light reflected from the convex mirror returns to its original position. The rotary force produced by the pressure is compensated by the magnetic force. Since the counterforce is directly proportional to the flowing current, it is possible to read the measurement signal in voltage form using a precision resistor.

This measuring principle is very precise thanks to its internal linearization and the omission of all mechanical movement with no measurable hysteresis error. These sensor systems can measure pressures from 30"H_2O to 2500 PSI (70 mbar to 170 bar) with accuracies up to $\leq 0.01\%$ of the measuring span.

Vibrating cylinder

With this sensor principle, developed in the nineteen-fifties, the pressure is directed into a metal cylinder. This hollow metallic body is then set to vibrate at its natural resonance (approximately 5 kHz) by exciter coils. When pressure is applied, this natural frequency changes in a non-linear but highly repeatable manner. A pressure-proportional, temperature-compensated output signal is produced using a digital linearization function integrated in the microprocessor.

This type of sensor is used solely for high-grade pressure measuring systems due to the great effort required for the cylinder and for the signal conditioning. Accuracies of between 0.01% and 0.02% of the measuring span are possible. With this system the sensor signal is affected by the gas density of the pressure medium; the sensor needs to be calibrated, therefore, for a suitable gas such as nitrogen or dry air. Pressure ranges up to 600 PSI (40 bar) can be measured.

Figure 1.48 Vibrating quartz sensor
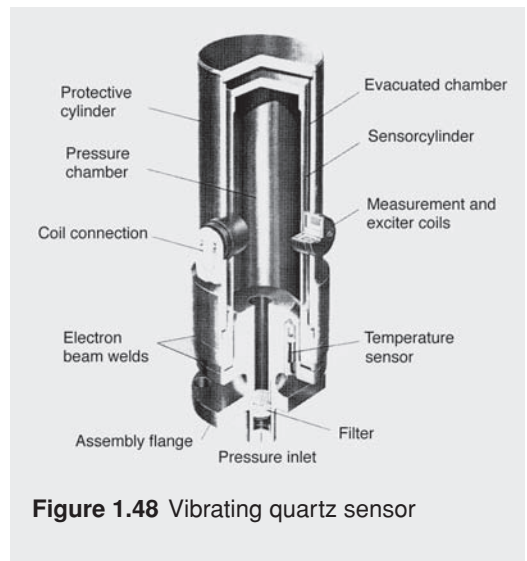
Vibrating quartz sensor

Vibrating quartz sensors are used for high pressures of up to 25,000 PSI (1600 bar). The heart of the pressure sensor is a cylindrical quartz crystal. The mechanical force caused by the pressure produces a change of resonant frequency in the quartz crystal, which forms part of a resonant circuit. A second quartz crystal, which is not pressurized, acts as reference. Its frequency output signal is used as a reference signal, which can be

used as the time basis of a frequency counter. It is also combined with the pressure-dependent frequency signal to form a pressure-proportional, non-linear output signal.

The temperature effect is extremely small since quartz crystals are used. However, a frequency signal from a temperature-dependent quartz crystal can also be used for exact temperature compensation.
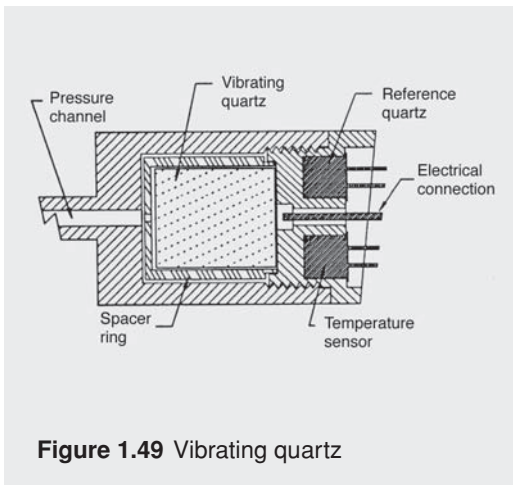
Figure 1.49 Vibrating quartz

Mechanical pressure measuring instruments with Bourdon tubes

1.4 Pressure measuring instruments with flexible measuring elements

The beginning of the 19th century saw the development of the first steam engines and steam-driven vehicles. The range of the liquid column pressure gauge invented by Otto von Guericke (1602 to 1686) could not be used for these machines. The water column which Otto von Guericke attached to his house was over 32 ft. high, but industrial advancements required much higher pressures to be measured. Mechanical loading by vibration had also increased. Therefore there was an urgent demand in the middle of the last century for more adequate measuring instruments. Today's familiar pressure measuring instruments with flexible elements (Bourdon tubes, diaphragms and capsules) were all developed within just a few years.

The first pressure gauge with a flexible measuring element was the **Bourdon tube pressure gauge**. Although invented in 1846 by a German engineer named Schinz (he made the first **measuring tubes** in 1845), it was the French engineer Bourdon who finally received a patent for this measuring element in 1848 and gave his name to this instrument. Two years later, in 1850, the mechanical engineer Bernhard Schäffer invented the **diaphragm pressure gauge**. As co-founder of the company Schäffer and Budenberg in Magdeburg, Germany, he influenced the field of pressure measurement for many years. The **capsule system** is a derivative of the diaphragm system.

Operating principle

If you blow into a rolled up paper tube such as a paper party streamer, it will "roll out" under the pressure. The flattened paper tube, pressurized from the inside, tries to regain its circular cross-section and straightens out. The same effect is used for metallic flexible pressure measuring elements.
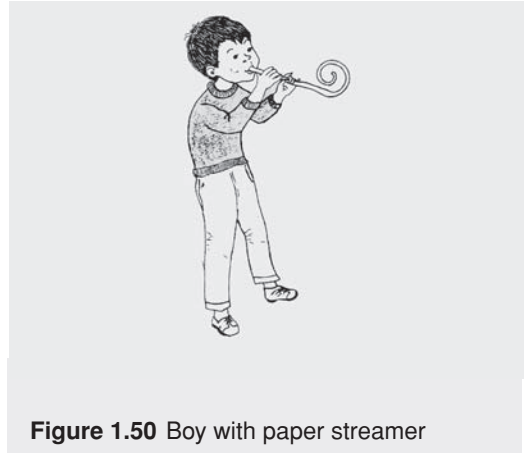
Figure 1.50 Boy with paper streamer

The pressure changes the shape of the measuring element in proportion to the applied pressure. Unlike the paper streamer, a metallic flexible pressure measuring element can only be deformed within a limited range due to the considerable material stresses involved.
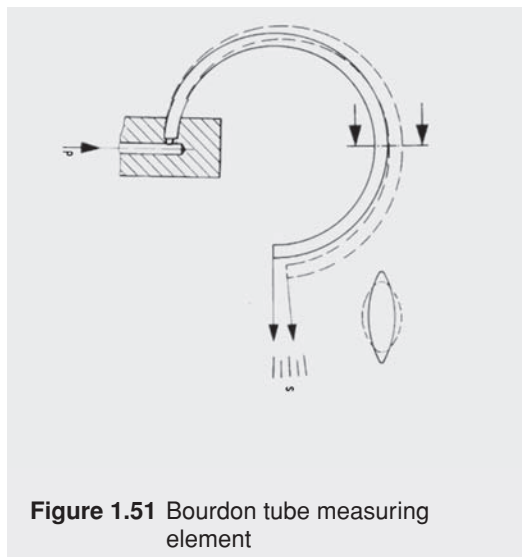
Figure 1.51 Bourdon tube measuring element

A **movement** is used to amplify the relatively small travel of the tube end and to convert it into a rotary motion. A pointer moving over a graduated dial indicates the pressure reading.
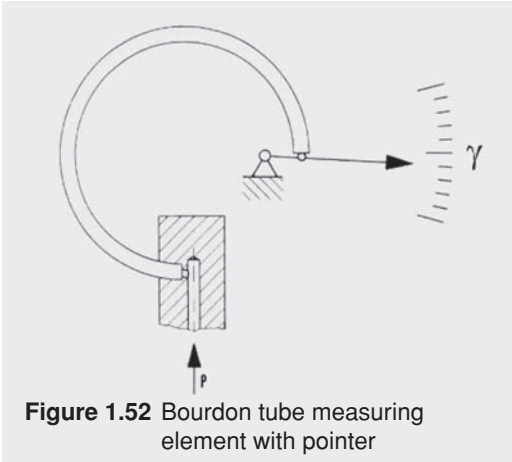
Figure 1.52 Bourdon tube measuring element with pointer

Basically, a pressure measuring instrument with a flexible element consists of three functional parts: a flexible **measuring element**, a **movement** and a **dial**.

The measuring element converts the pressure **P** into a displacement **S**. The movement amplifies the displacement **S** and converts it into an angle of rotation γ. The dial is marked with a graduated scale to convert the pointer position into a pressure reading.

For protection, the three functional parts are installed in a **case**.

1.4.1 Flexible measuring elements

The flexible measuring elements in common use today are shown in Figure 1.54. Generally speaking, they are **Bourdon tube** and **diaphragm measuring elements** with various designs.

1.4.1.1 Bourdon tubes

Bourdon tubes are made from metal tubing with a circular cross-section. The cross-section of the tubing is flattened and then the flattened tubing is formed into a circular or helical shape.

When a pressure is applied to the inside of the tube, the flattened section tries to regain its former circular cross-section.

Radial tensions in the tube lead to an increase of the radius r_0 and to a displacement s of the tube end. The displacement of the end point EP_0 to EP_1 can be regarded as a movement around the **base point P**. In a circular tube section the radius remains constant - a fact well noted by plumbers. When the tube is flattened (b > a), the radius is reduced. The fundamentals for calculating such measuring elements have been published by Dr. W. Wuest and others. They are presented next in abbreviated form.
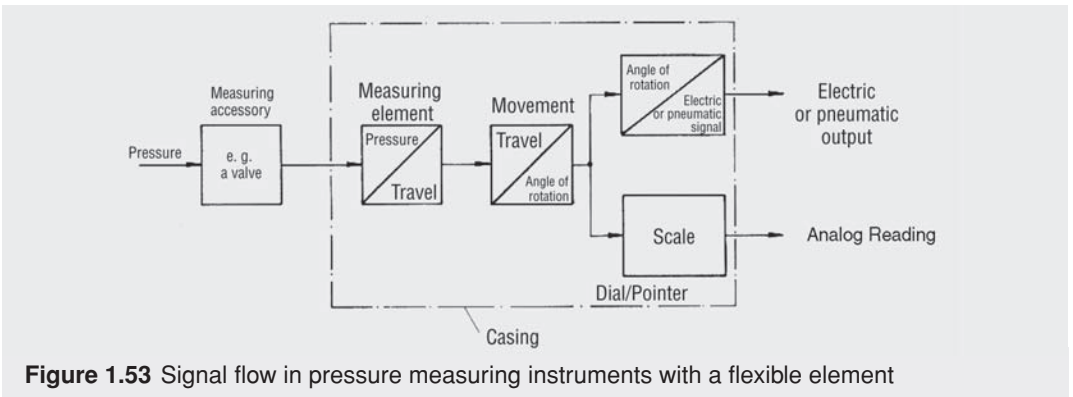
Figure 1.53 Signal flow in pressure measuring instruments with a flexible element
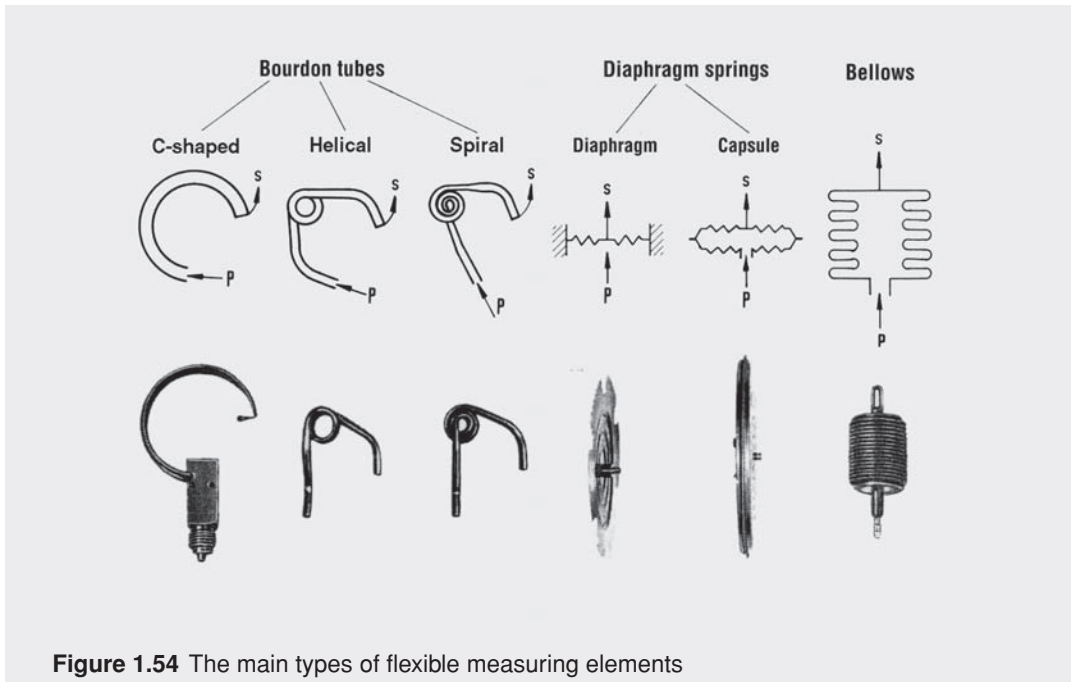
Figure 1.54 The main types of flexible measuring elements
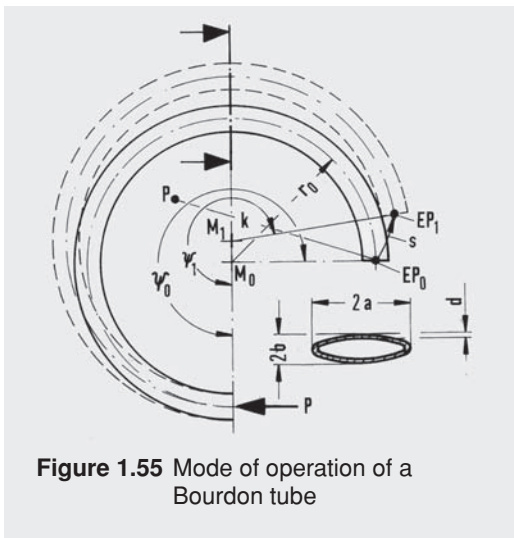
Figure 1.55 Mode of operation of a Bourdon tube

Since the wall thickness of the tube varies considerably depending on the pressure range, a distinction has to be made between low-pressure measuring elements with $\lambda > 1$ and high-pressure elements with $\lambda < 1$. The coefficient λ is calculated from

$$\lambda = \frac{a^2}{d \cdot r_0} \tag{1-30}$$

The main factor for pressure measurement is the spring displacement, which is a measure of the pressure. Its magnitude can be calculated as a function of the relative change of curvature ω.

$$s = \omega \cdot \Psi_0 \cdot k' \cdot r_0 \tag{1-31}$$

The relative change of curvature is

$$\omega = f_{(N,H)} \cdot \frac{a^4}{bd^3 \cdot E} \cdot p \tag{1-32}$$

where $f_{(N,H)}$: is the coefficient of the change of curvature of low-pressure or high-pressure spring elements.

Since measuring element displacement is just 0.08 to 0.28 inches (2 to 7 mm), the values must be magnified with a mechanical movement. The greater the restoring torque **M** of the spring end, the easier the transmission.

The **restoring torque** is

$$M = (\Psi_0 - \Psi_1) \, f_M \cdot \frac{E \cdot J}{r_0 \cdot \Psi_0} \qquad (1\text{-}33)$$

where **J** is the moment of plane area of the tube cross-section and f_M the coefficient of the spring rate constant.

Like other components, it is important for flexible measuring elements to not be loaded beyond their acceptable limits. The maximum bending stresses of Bourdon tubes are limited by the internal fibers of the "top" side.
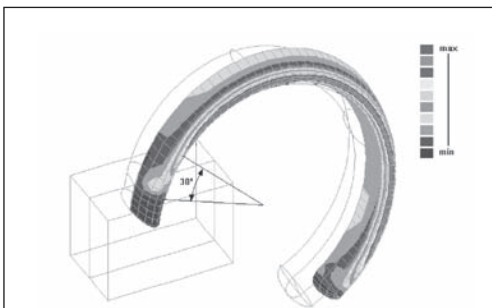
Figure 1.56 Material stresses in a circular shaped tube subjected to internal pressure; maximum loading over the entire length of the "top" edge, except at the ends

The maximum stress is determined by

$$\sigma_{max} = f_{(N'H')} \cdot (\frac{a}{d})^2 \cdot p \qquad (1\text{-}34)$$

where $f_{(N'H')}$ is the coefficient of the bending stresses of low-pressure or high-pressure springs.

Figure 1.56 shows the stress characteristic of a Bourdon tube loaded with internal pressure in the form of a **finite element method** (FEM) diagram. The beginning and end of the Bourdon tube are subjected to low stresses. This is due to the reinforcement of the oval profile by clamping the element in the holder and closing the element with the end cap. This also means that the loss of strength of the cold-hardened spring material in the welding zone is not a critical factor.
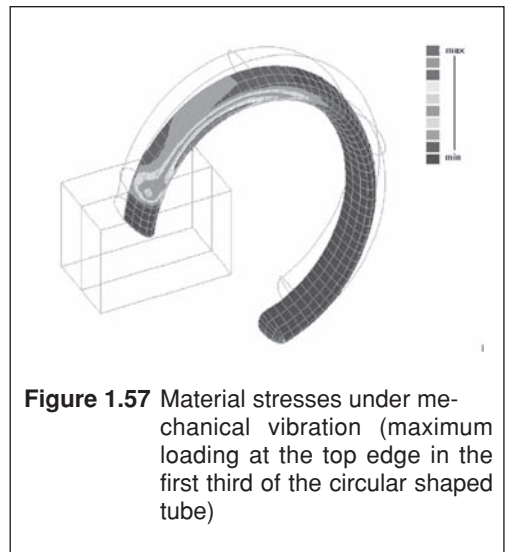
Figure 1.57 Material stresses under mechanical vibration (maximum loading at the top edge in the first third of the circular shaped tube)

Figure 1.57 shows the stress characteristic of the same tube when it is not subjected to internal pressure but instead loaded by external (mechanical) forces such as shock or vibration. The increase in stress toward the tube base should be noted. A mixture of both factors is likely in today's industrial applications.

These material stresses in the top edge occur when the movement of the tube end is unrestrained. An important factor in many industrial applications is **protection against accidental overloading** and the protective measures available for Bourdon tubes. Figure 1.58 shows the stress diagram of a Bourdon tube with a rated pressure of 30 PSI (~2.5 bar). Curve "a" shows the stress function of an unrestrained element.

a	=	σ_{bmax}	of the unrestrained measuring element
c,c'	=	σ_{bmax}	of the restrained measuring element

Figure 1.58 Bending stress characteristic of Bourdon tubes with and without restraint
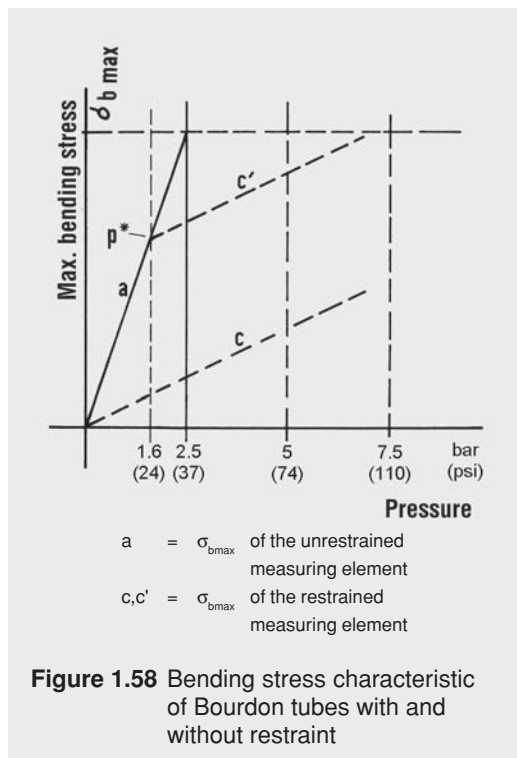
Curve "c" shows the stress with a restraint on the end of the tube. The maximum bending stress at the rated pressure is approximately 25% of the stress of the unrestrained measuring element. If the operating range of the measuring element is limited at a given point, for instance at p* = 25 PSI (~1.6 bar), the material stress will first follow curve "a" of the unrestrained element and with a further pressure increase it will rise along curve c', which is the stress curve of the restrained element.

This method can be used in practice for an overload capacity of up to five times the rated pressure. It cannot be used, however, as a protection against frequent or continuous overpressures. For those cases, other alternatives should be discussed with the manufacturer.

The geometry of the tube elements and their tolerances has a great effect on the aforementioned calculated results. This requires that manufacturers adhere to strict product development, quality, and inspection procedures in order to produce Bourdon tubes that meet the demanding requirements of today's industrial applications.

The design principles apply to all three forms of Bourdon tube elements; C-shaped, helical and spiral. However, spiral tubes are somewhat of an exception since the radius r_0 changes along the stretched tube. At constant cross-section the largest bending stresses are found at the point with the largest radius, and they decrease as the radius shrinks. Since the dimensions have to be based on the point with maximum loading, production of spiral tubes is not economical. For this reason, instruments with spiral tubes have generally been replaced by those with helical tubes.

The transition from a C-shaped to a helical measuring element depends on the loadability of the tube materials used. The yield limit cannot be fully reached for two reasons, one to do with dimensional reasons and the other with life expectancy. Both are considered below. The time-related characteristic of the loading plays a role in the maximum loading of the materials while avoiding fracture.

There are three distinctive types of loading: static, dynamic, and alternating load (Figure 1.59).

The maximum allowable material stress is determined from a stress-cycle diagram which is different for each type of material and load type.

Pure alternating loads, with positive and negative stresses, alternate above and below atmospheric pressure. If the loading does not cross above or below atmospheric pressure, then it is considered either static loading, dynamic loading or static loading with embedded alternating loading.

To avoid fatigue fracture caused by dynamic loads, only 40 to 50% of the yield limit is used. For Bourdon tubes, the end of the measuring range is at approximately 80% of the yield limit.

Figure 1.59 Types of loads on components

a = maximum load deflection for alternating load

b = maximum load deflection for dynamic load

Figure 1.60 Stress cycle diagram
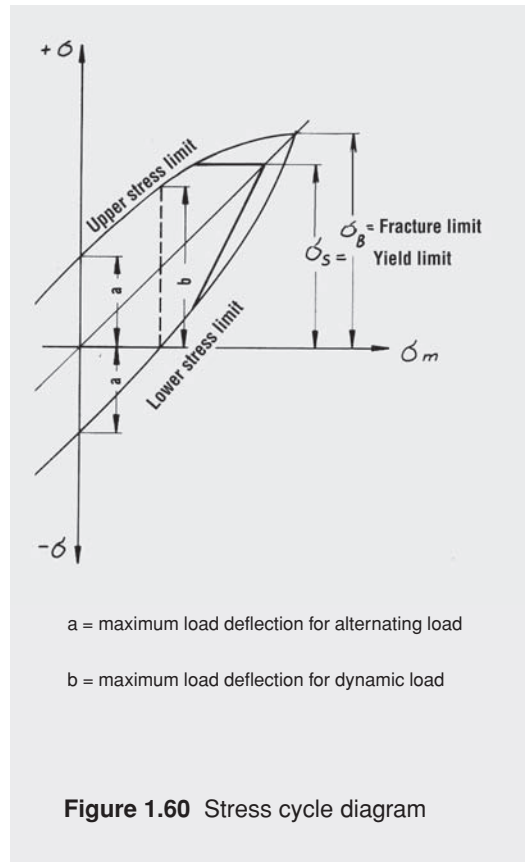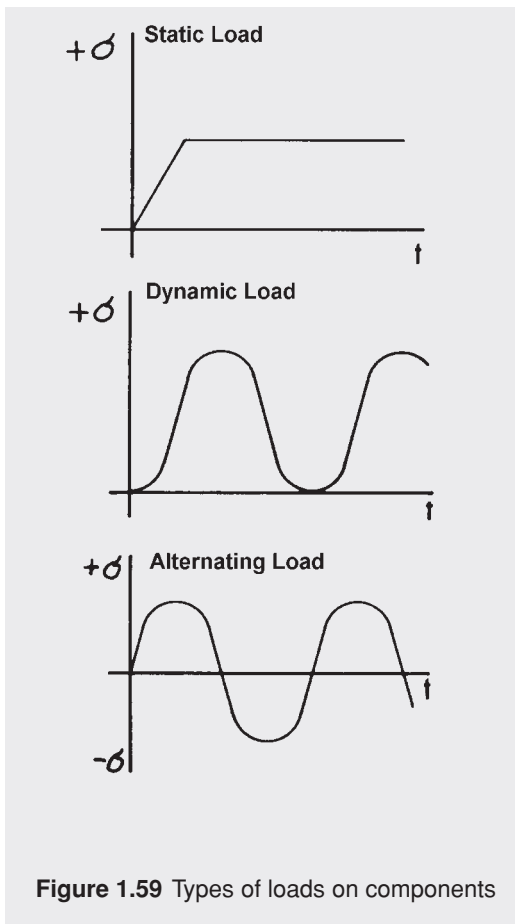
These problems are addressed in the national and international standards for pressure gauges which recommend selecting a pressure gauge range that is higher than the working pressure. The bigger the difference between the working pressure and the full scale range of the gauge, the longer the life expectancy.

In a series of Bourdon tubes with identical dimensions, Bourdon tubes with higher full scale pressure ratings reach more of their yield limit. Figure 1.61 shows the correlation between maximum material stress at 1.3 times the full scale range and the shape of the Bourdon tube.

For each Bourdon tube design (i.e. C-shape or helical), the wall thickness, not the overall tube dimensions, changes to increase the pressure range. Once the yield limit is reached for that tube design, a different design must be used to reduce the stresses as is shown in Figure 1.61. The LP

(low pressure) design is the C-shape. For higher pressures HP (high pressure) the helical design is used. Finally, for even higher pressures EHP (extra high pressure) a tube material with higher yield limits is used.

Bourdon tube production has certain inherent uncertainty which cannot be changed by the instrument manufacturer, i.e. surface defects on the inside of the tube shorten the **dynamic life** from their notching effect. Random tests on tube inventories limit the extent of this problem but they cannot eliminate it entirely.

The **hysteresis characteristic** of a material plays a major role in material loading. When a material is loaded with increasing stresses, resulting in a stretching of the material, it will return to its initial value along a curve that is above the "rising" curve (Figure 1.62).
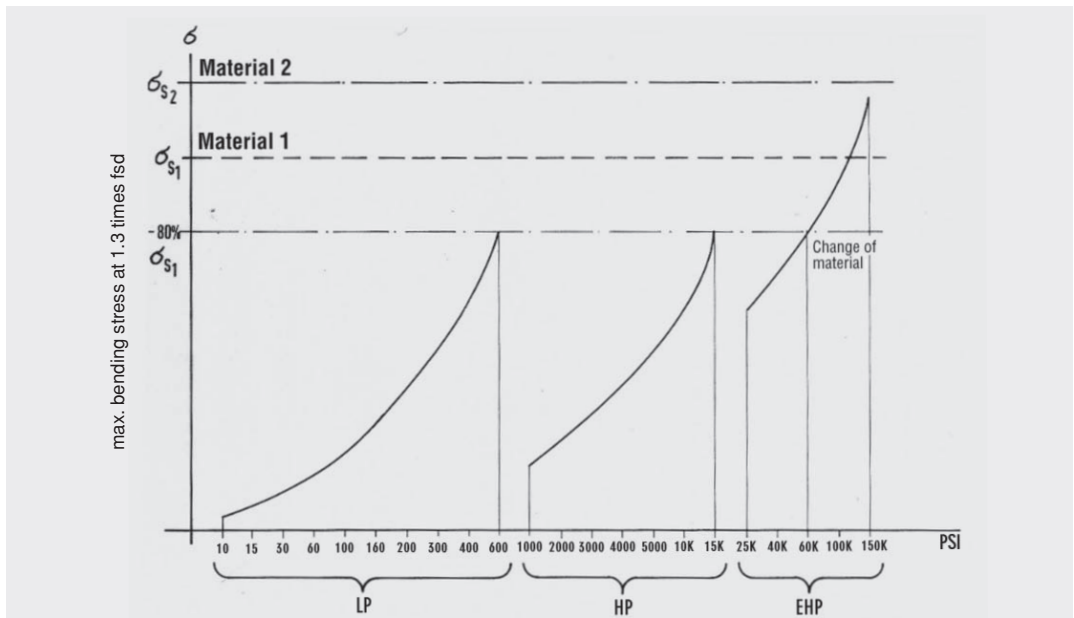
Figure 1.61 Maximum yield limit utilization in Bourdon elements at 1.3 times full range (fsd.)
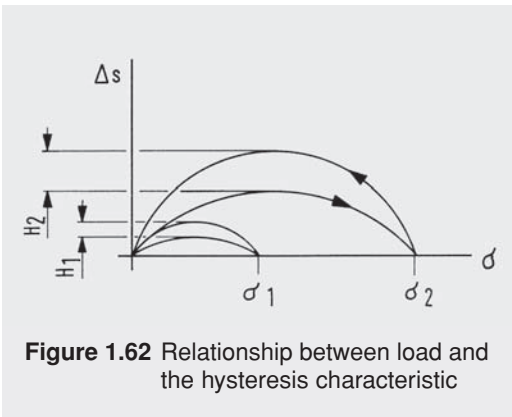
Figure 1.62 Relationship between load and the hysteresis characteristic

The difference in readings between an "upscale" and "downscale" movement is known as hysteresis. It is the pointer which returns to its initial zero position. The magnitude of the hysteresis is a function of several effects such as the magnitude of the load, the quality of the tube surfaces and the material structure. The hysteresis characteristic of flexible tubes can be changed by **heat treatment** specific to various materials and their intended uses. Depending on the method that the tube is attached to the socket such as soldering, brazing, threading or welding, this heat treatment is performed on the tube alone or on the complete measuring element. Welded systems are heat-treated to reduce localized strains in the weld zones, which would adversely affect the hysteresis characteristic.

Hysteresis should not be confused with a permanent deformation of the measuring element after excessive loading. **Permanent deformations** would mean that the pointer would not return to its zero position after removal of the load. This can also be caused in certain cases by excessive shock loads.

Tubes with various cross-sections have been developed to meet special requirements such as improved linearity, shock resistance or long life. They have been made out of assorted materials and with varied radii.

Deciding on the best shape of the tube is also a matter of ecomomics since some of the cross-sectional samples shown below are more difficult to manufacture than others.

Bourdon tube materials standard in the industry are brass/bronze, steel, 316 stainless steel, and Monel. It is difficult to manufacture tubes in other materials due to the fact that purchasing the material in the required size and strength is not cost-effective for the small quantities demanded.

As an example of the large number of tube dimensions used, Figure 1.64 shows a series of Bourdon tubes needed for 2" pressure gauges in low-pressure (LP) ranges.

Because of its special design, a Bourdon tube pressure gauge's temperature characteristic depends almost entirely on the **temperature-related** change of the **modulus of elasticity** of the
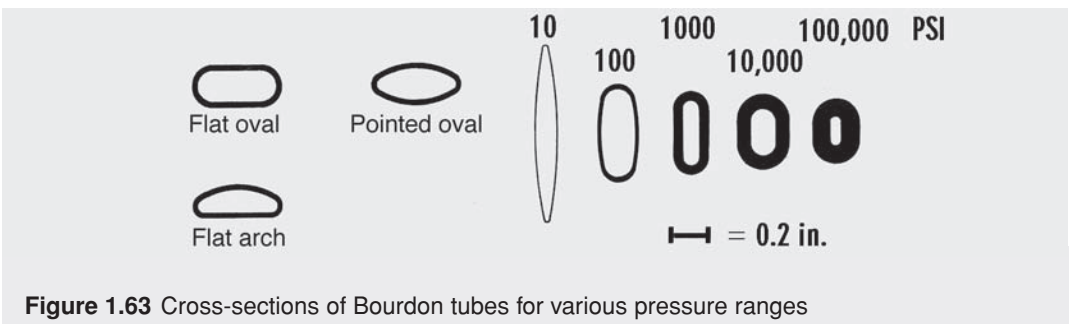
Figure 1.63 Cross-sections of Bourdon tubes for various pressure ranges
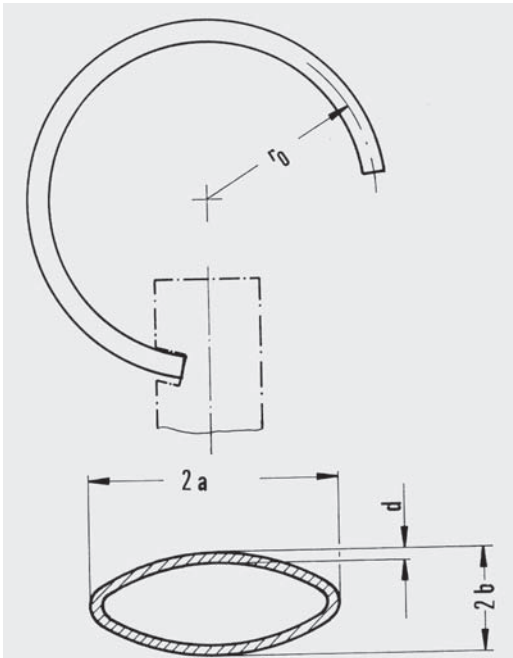
Measuring range [PSI]	Profile dimension [in]		
	2 a	2 b	d
10	0.5335	0.0984	0.0055
15	0.5276	0.1063	0.0059
30	0.5217	0.0945	0.0079
60	0.4055	0.1043	0.0071
100	0.4094	0.1063	0.0118
160	0.4114	0.1063	0.0118
200	0.4016	0.1063	0.0138
400	0.3996	0.1220	0.0157
600	0.3976	0.1201	0.0197

Figure 1.64 Various C-shape Bourdon tube dimensions

Bourdon tube. The relationship can also be seen in the displacement of the measuring element:

$$s = f(p) \cdot \frac{1}{E} \qquad (1\text{-}35)$$

A temperature increase leads to a smaller modulus of elasticity and therefore to a larger element displacement, and vice versa.

The temperature-related change of length of an instrument's materials results in an enlargement of the entire measuring system. If the same materials are used for all components, however, there will be no displacement of the tube end relative to the movement and therefore no temperature-related error at "zero" pressure.

Life, accuracy and temperature characteristic all depend on the selection of dimensions and material. Bourdon tubes with a small diameter, for example, are better for vibrating systems such as compressors since they have a smaller mass. For applications with constant pressure fluctuations such as on hydraulic presses, a large Bourdon tube would be best suited because of its smaller deformation and reduced material fatigue.
A Bourdon tube with a circular tube cross-section is more resistant to mechanical shocks, but flat tube sections are easier to manufacture.
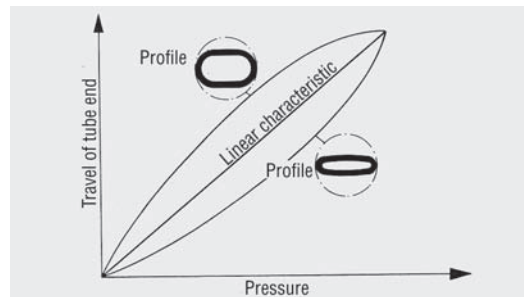
Figure 1.65 Pressure-displacement curves of Bourdon tubes

The pressure-displacement curve shows the typical correlation between the shape of the section and the type of travel (Figure 1.65). Circular cross-sections result in a convex curve, flat sections in a concave curve. These nonlinearities can be significantly reduced by making adjustments to the movement.

The pressure-displacement characteristic cannot be pushed too far. If an excessive elongation takes place with an overpressure, the material will undergo permanent deformation. This is true of all flexible pressure measuring elements. A pressure measuring instrument with a permanent deformation does not return to zero after venting the pressure.

The **Bourdon tube tip-travel curve** shown in Figure 1.66 shows the point at which permanent deformation occurs; it is marked "A". In real applications a pressure gauge should never be loaded up to this limit. The maximum limit for static loading (i.e. constant pressure) is marked "B" on the curve. This limit corresponds to the full scale range printed on the dial.

When the measured pressure is dynamic (i.e. alternates up and down) , it is important that the measuring element's **static-load pressure limit** is never reached in order to elminate the risk of material fatigue. The limit decreases as the number of load cycles increases.

Most standards for pressure measuring instruments set the minimum number of dynamic load cycles at 200,000. To meet this goal, the maximum pressure "C" should not exceed 90% of the measuring element's static load limit.

In some applications, the maximum operating pressure is not set by the load limits of the measuring element but instead by the load limits of other components in the pressure system (such as piping) and those pressure limits may be specially highlighted by a red mark on the dial.

Figure 1.66 Maximum pressure limits of Bourdon tubes
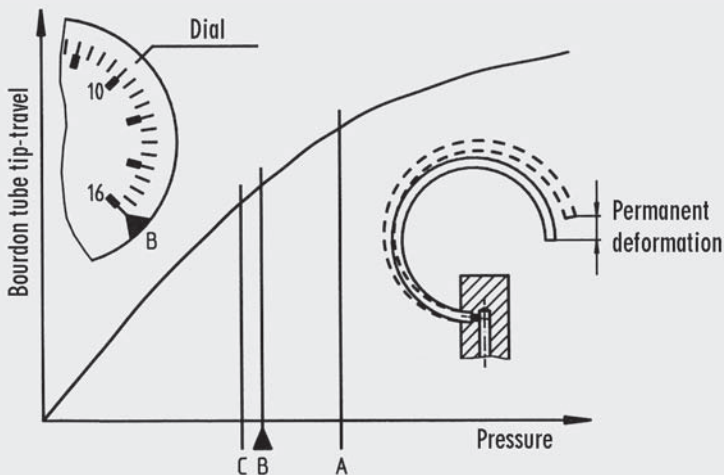
A: Beginning of permanent deformation
B: Maximum pressure under static load
C: Maximum pressure under dynamic load

The method used to attach the Bourdon tube and the connection varies based on the Bourdon tube material and the pressure range. Bourdon tubes made with copper alloys are usually attached by **soldering**. For some high pressure ranges or when the gauge will be used in high operating temperatures, **brazing** is used instead due to the tendency of solders to creep.
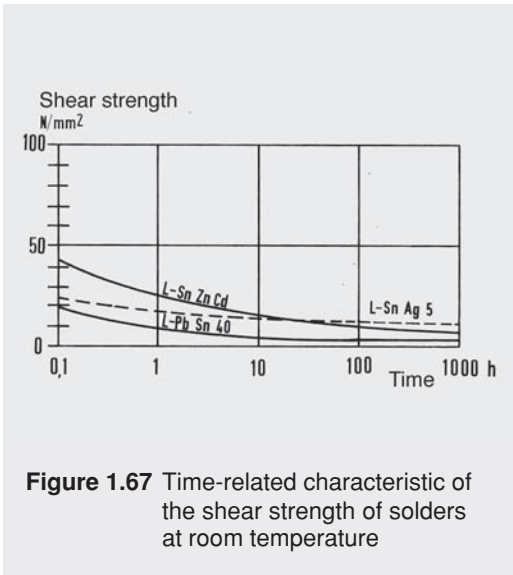
Figure 1.67 Time-related characteristic of the shear strength of solders at room temperature

Figure 1.68 Solder shear strength at 1000 hours as a function of temperature

Figure 1.67 shows the shear strength of three typical solders at a constant temperature of 68 °F as a function of time.

The high short-time strength value of a solder should never be used to specify a solder type. As Figure 1.67 shows, it is important to use the long-time shear strength value. The long-time strength value is 10 times lower that the short-time value, but after 1000 hours it remains nearly constant. However, even the long-time shear strength is temperature-dependent, as shown in Figure 1.68.

Of course, these factors are based a perfect solder joint without cavities. For safety reasons, solder joints at WIKA are based on the long-time shear strength value (1000 hours) at 125 °F for 2.5 times the full scale range of the instrument.

Brazing is subject to the same problems as soldering, but at a much higher level of strength and temperature.

Measuring elements and connections made of low-alloy or high-alloy steel are joined by welding in an inert gas atmosphere. Welding provides the most reliable joint as long as the pressure range does not exceed the weld joint strength (i.e. pressures above 25,000 PSI). For those extremely high pressures, the Bourdon tube is attached to the connection by special threaded joints (Figure 1.69). By limiting the size of the area under pressure, it is possible to keep these extreme loads safely under control.

In summary, the most frequently used measuring elements are Bourdon tubes, which come in various shapes depending on the specific pressure range. For pressures up to around 1000 PSI, C-shaped tubes are generally used. Above 1000 PSI they are helical. Spiral measuring elements are used only in special cases.
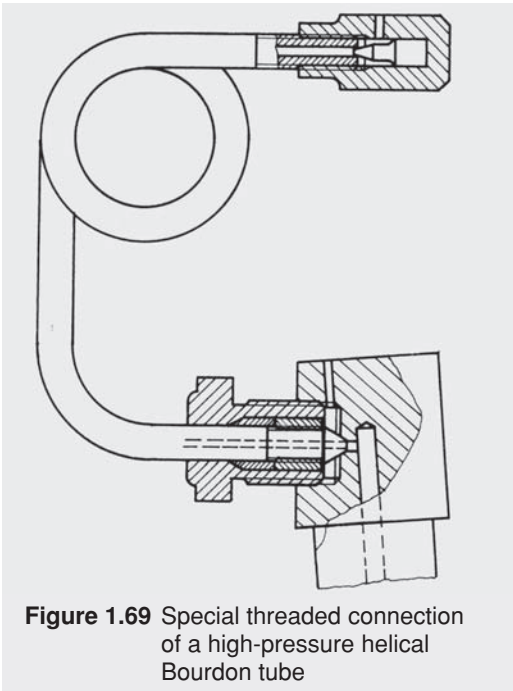
Figure 1.69 Special threaded connection of a high-pressure helical Bourdon tube

Compared to diaphragm and capsule type measuring elements, Bourdon tubes have the following advantages:

- They cover pressure ranges from just 0/10 PSI up to very high pressure ranges of 0/150,000 PSI.

- They have a large, measurable tip travel that is linear.

- They have accuracies up to ASME Grade 4A (±0.1% of span).

- They are easy to produce.

- They are easily connected to other wetted-part components. They can be soldered, brazed, welded or threaded, depending on the material and pressure range.
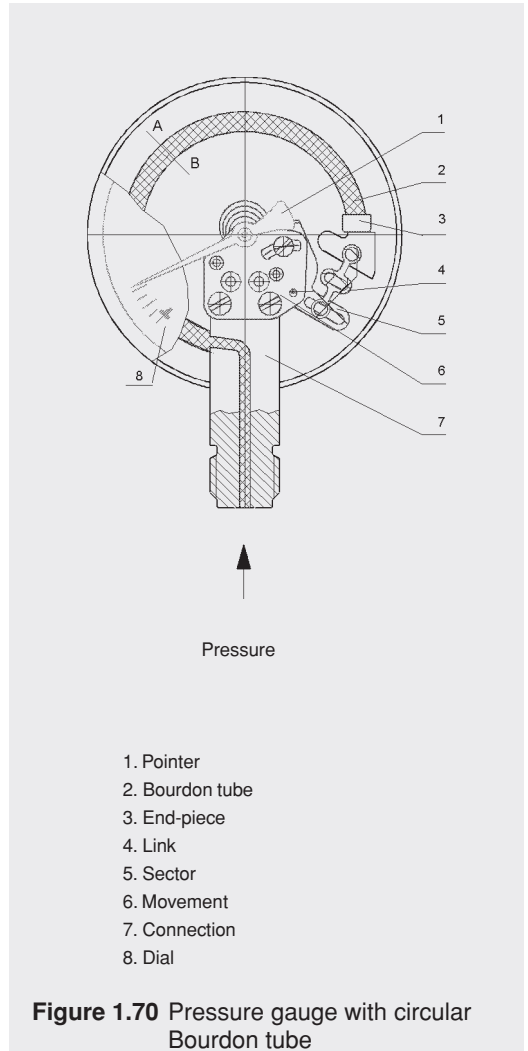
Pressure

1. Pointer
2. Bourdon tube
3. End-piece
4. Link
5. Sector
6. Movement
7. Connection
8. Dial

Figure 1.70 Pressure gauge with circular Bourdon tube

1.4.1.2 Diaphragm measuring elements

Diaphragm measuring elements such as **flat diaphragms** and **capsules** are commonly used for low pressures from 0/0.5 "H_2O up to around 0/400 PSI. A typical application is liquid level measurement in open tanks.

1. Bottom housing (threaded)
1A. Bottom housing (flanged)
2. Pressure chamber
3. Upper housing
4. Diaphragm
5. Sealing o-ring
6. Bolts
7. Nuts
8. Push rod
9. Movement
10. Pointer
11. Dial

Figure 1.71 Pressure measuring instrument
with diaphragm

Diaphragms

In diaphragm elements, measurements are taken from the elastic deformation **s** of the diaphragm, which is held by its edges and loaded on one side. This deformation is converted by known methods into a rotary movement.

Due to their shape and position, diaphragms have high mechanical resistance and are less shock-sensitive.

They are commonly made of steel or 300-series stainless steel. For aggressive fluids, special corrosion-resistant materials such as tantalum, titanium, Hastelloy etc. are used, or the materials are coated with PTFE or similar materials. Open flanged connections are used if the process fluid is highly viscous, crystallizes or is contaminated.

Deflection calculations for diaphragms are more complex than those for Bourdon tubes. Haringx developed a method that can be reduced to a simple numeric formula.

$$s = \frac{3}{16} \cdot \frac{R^4}{E' \cdot d^3} \cdot p \qquad (1\text{-}38)$$

$$\text{with } E' = \frac{E}{1 - \mu^2}$$

Figure 1.72 Deflection calculation for
a flat diaphragm
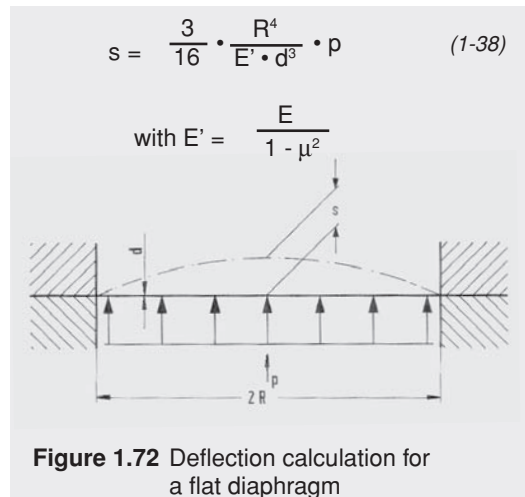
The starting point is the deflection of the flat, edge-clamped plate, which shows the importance of the radius **R** and diaphragm thickness **d**.

Flat diaphragms have linear characteristics at a given pressure **p** and a displacement **s** for small deflections only. Therefore, they are usually used in combination with electrical and capacitive add-ons. Mechanical pressure measuring instruments need a displacement of between 0.04 and 0.12 inches (1 to 3 mm).

With those deflections, flat diaphragms are generally non-linear. However, by adding convolutions to the diaphragm, the linearity can be significantly improved. Figure 1.73 shows the effect of the depth of the diaphragm convolutions on the displacement with a constant number of convolutions.

Figure 1.73 Characteristic curves of diaphragms as a function of the depth of convolution
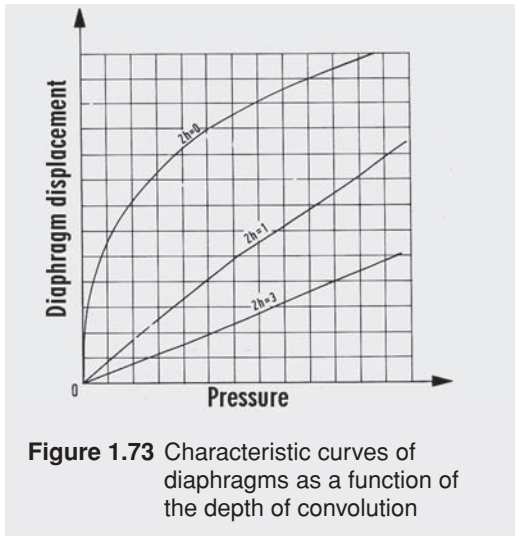
The cross-section of the convolution, whether sinusoidal, sawtooth or trapezoidal, has little effect on the displacemant and linearity. Figure 1.74 shows a series of practical cross-sections.

Sinusoidal corrugation

Corrugation with overpressure protection

Sawtooth corrugation

Figure 1.74 Common convolution cross-sections
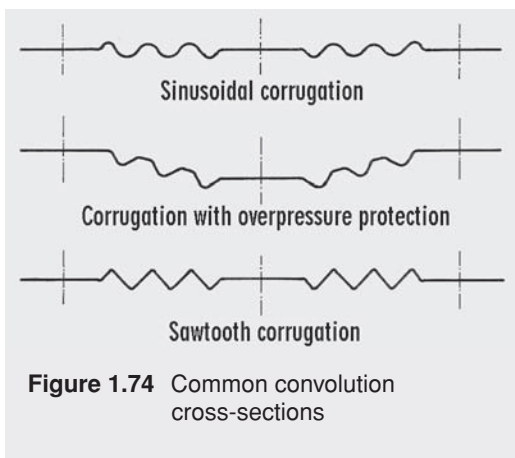
The calculation formula for convoluted diaphragms according to Haringx differs from the formula for flat diaphragms simply by adding a reduction coefficient k_{red}:

$$s = \frac{3}{16} \cdot k_{red} \cdot \frac{R^4}{E' \, d^3} \cdot p \qquad (1\text{-}37)$$

The coefficient k_{red} specifies the effect of the number of convolutions and their depth.

$$k_{red} = \frac{s}{l} \cdot f(q,p) \cdot g\left(\frac{dR}{l^2}, \frac{e}{l}, \frac{c}{l}, p\right) \quad (1\text{-}38)$$

Section X

Figure 1.75 Calculation for diaphragms with concentric convolutions
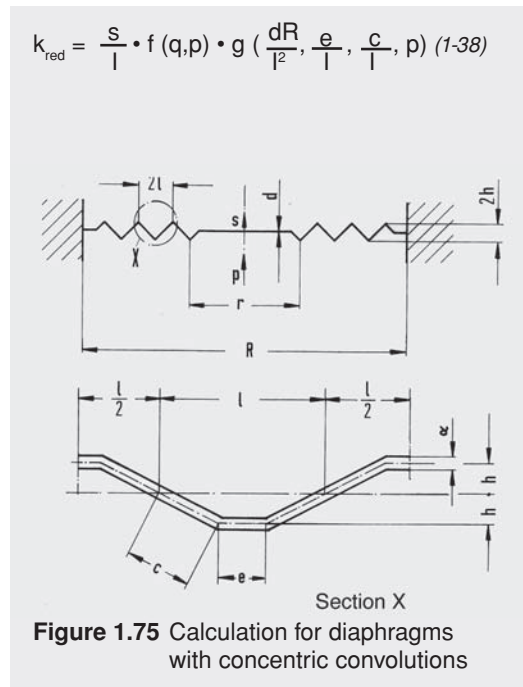
Like all loaded components, the maximum dynamic load limit of a diaphragm must not be exceeded. The same basic factors that apply to Bourdon tubes also apply to diaphragms.

Because of their complexity, other mathematical relationships such as those for material stresses or the linearity of spring deflection, are not considered here. Those relationships can be obtained from more in-depth material available on the subject.

The best way to determine where the maximum stresses occur in a diaphragm under pressure is by using and FEM (Finite Element Model) diagram. The lowest stresses occur at the center of the diaphragm and the highest occur at the outermost convolution.

Particular attention is paid to the effect of the **peripheral shaping** on the pressure-travel characteristic of the diaphragm; see Figure 1.77.

Unlike Bourdon tubes, the temperature characteristic of a diaphragm is less dependent on the modulus of elasticity and more dependent on the effect of the peripheral clamping. This also causes a temperature error even at "zero" pressure which can amount to more than twice the error of Bourdon tubes. The hysteresis is also generally higher than for Bourdon tubes.

However, an important advantage is the high stiffness of the diaphragms even for lower pressures. It reduces the friction problems in the movement and its effect on instrument accuracy.
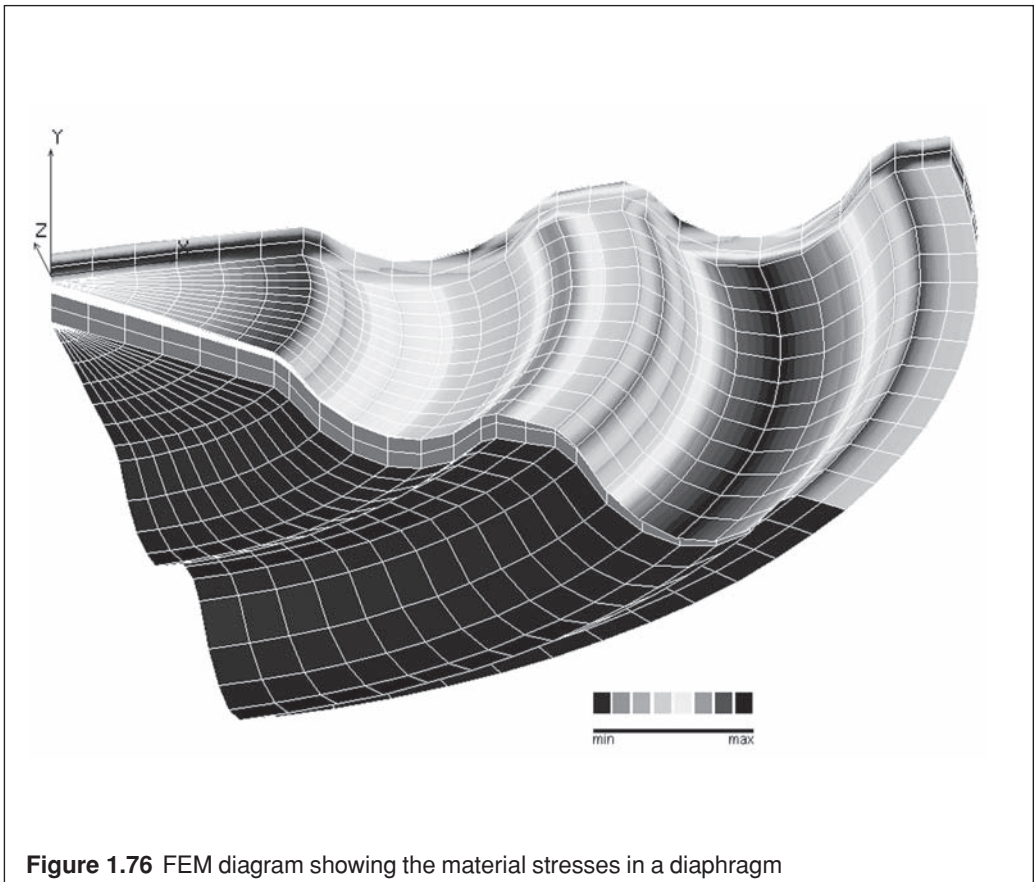
Figure 1.76 FEM diagram showing the material stresses in a diaphragm
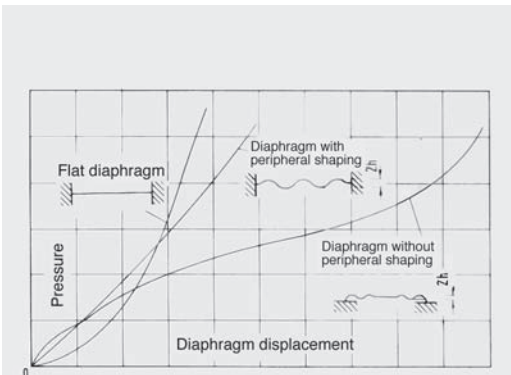
Figure 1.77 Pressure-displacement curves of diaphragms

Figure 1.78 Diaphragm overload protection using a solid support

Diaphragms for pressure instruments are generally made of high-alloy steels such as 316 stainless steel. When other materials are used, flexible coatings or linings are used to protect the diaphragm from corrossive media.

Diaphragms are easier to protect from overpressure than Bourdon tubes. The most common form of protection is by using a specially shaped **diaphragm bed** in the upper housing that prevents the diaphragm from deforming; see Figure 1.78. This diaphragm bed can be made of a high-fiber resin or, for higher temperatures, by machining the bed directly into the top housing.

The use of a diaphragm bed for overpressure protection is now being used more and more in place of hydraulically supported diaphragms which are described next.

Hydraulically supported diaphragms can protect diaphragms from overloading up to 100 times the measuring range. For this type of support, the "diaphragm bed" is formed by a liquid (Figure 1.79) and the diaphragm (1) consists of two diaphragms that are securely joined together.

The pressure being measured (2) acts on the lower diaphragm (1) and causes a deflection of the diaphragm. The chamber (3) between the two diaphragms is filled with a transmitting liquid. Both diaphragms are securely joined at their center by a rod (4). If an overpressure occurs, the seal on the coupling rod closes and prevents the transmitting liquid flow. Since the transmitting liquid is incompressible, the lower diaphragm is firmly supported and will not deformed. The travel is transmitted to the movement by the rod (5).
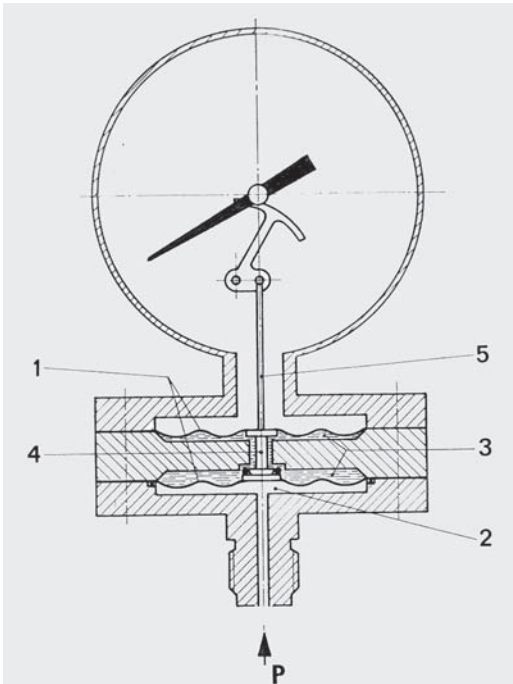
Figure 1.79 Diaphragm overload
protection using
hydraulic cushioning

↑ Pressure

1. Capsule support   5. Dial
2. Pressure chamber   6. Pointer
3. Capsule   7. Window
4. Movement   8. Zero correction

Figure 1.80 Capsule pressure measuring
instrument

Compared to Bourdon tubes, the displacement of the measuring element is very small. For this reason, quality and tolerances of this resilient material must meet very exacting specifications. The measuring characteristic of a diaphragm depends greatly on the type of peripheral clamping and on the seal.

For very low pressures the diaphragms are extremely thin, reducing their stability and making their production difficult. Capsules are preferred, therefore, as measuring elements for very low pressures. Basically they are a special type of diaphragm.

Capsules

A capsule consists of two diaphragms that are welded or soldered together around their outer edge. The center of just one capsule half is supported in the case so that both halves can move freely. This design doubles the displacement of the diaphragm, allowing smaller pressures to be measured without any reduction of the wall thickness. Capsule elements are currently being used for the measurement of flowing gases, i.e. in chambers or fans.

Even micropressures in the range of 0 to 0.5"H_2O can be measured. The necessary displacement is accomplished by connecting several capsules in series (Figure 1.82). Evacuated capsules are used as measuring elements for **aneroid barometers** in the measurement of atmospheric air pressure.

Figure 1.81 Movements of a capsule measuring element

Figure 1.82 Several capsules connected in series to increase the travel

The advantages and disadvantages of capsule elements are similar to those of diaphragms. Closing the inlet when the nominal pressure range is exceeded allows capsule elements to withstand high overloads.

Figure 1.84 Overload protection of a capsule measuring element

A pin with a gasket is attached to one half of the capsule. In the event of excessive pressure in the chamber, this pin closes the inlet and at the same time supports the center of the upper diaphragm, increasing the load-bearing capacity significantly.

The calculation basis is the same as for diaphragms (see Figure 1.77).

The temperature concerns associated with the peripheral clamping of diaphragms do not exist with capsule measuring elements. Hence the temperature characteristic is conditional here, too, mainly on the change of the modulus of elasticity.

1 Measuring element (aneroid capsule)
2 Base plate
3 Leaf spring
4 Lever
5 Pointer
6 Thread

Figure 1.83 Principle of an aneroid barometer

The materials used are copper alloys and stainless steels. The center clamping results in lower shock and vibration resistance values for the capsule than for diaphragms.

1.4.1.3 Bellows

Bellows are used where a large displacement is required in a restricted space. Bellows are thin-walled cylindrical containers with deep corrugations in their periphery. When pressure is applied, the length of the bellows changes. Depending on the application, a supporting spring can be installed inside the bellows. Bellows are notable for their good linearity. Generally they are used in the range from 0 to 2.5 "H_2O and 0 to 10 PSI.
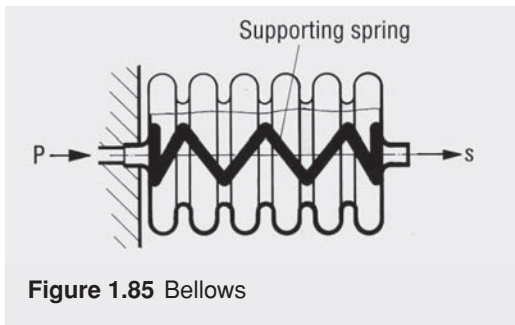
Figure 1.85 Bellows

Their use for pressure measurement purposes is limited to certain instrument types. One area in which they are indispensable is the hermetic transmission of travel from pressure chambers. Formulae for their calculation are available in conjunction with diagrams for determining essential coefficients.

1.4.2 Movements

A measuring element converts pressure into displacement. The movement measures the displacement and converts it into a rotation. A movement consists of a combined **lever** and **gear**. The linear displacement of the measuring element is converted into a pointer rotation. A displacement of 2 mm, for example, can be converted into the customary rotary movement of 270 angular degrees. Depending on how big the displacement is, movements with various mechanical advantages are used.

1. Link
2. Link adjustment (control point)
3. Toothed segment
4. Segment opening
5. Pointer shaft
6. Pointer
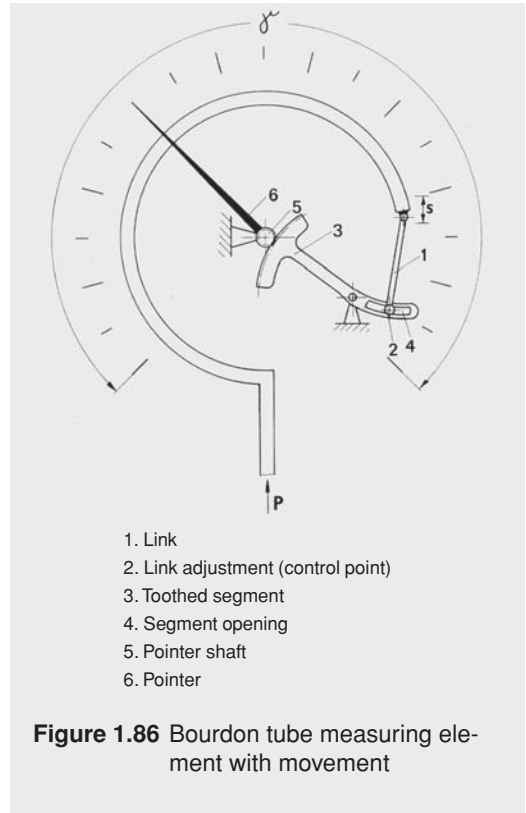
Figure 1.86 Bourdon tube measuring element with movement

Adjustment of the link adjustment point in the segment opening allows fine adjustment of the pointer travel to 270 angular degrees.

The movement consists of two platens with spacer columns, in which the pointer shaft and the toothed segment rotate (Figure 1.87).

A hairspring ensures that the same faces and toothed flanks always mesh during the movement sequence.

1. Link
2. Toothed segment
3. Platen
4. Pointer shaft

5. Segment slot
6. Shoulder screw
7. Hairspring
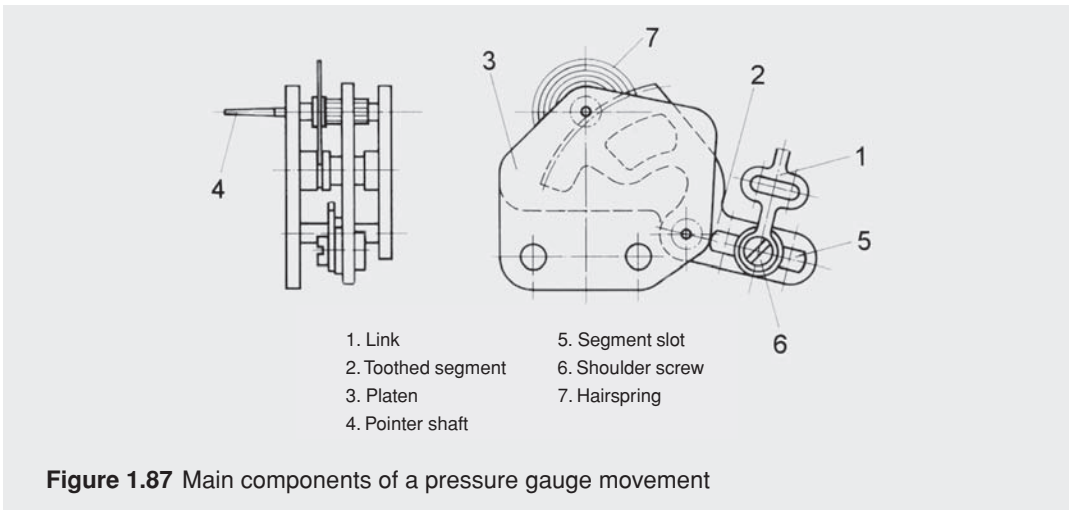
Figure 1.87 Main components of a pressure gauge movement

This avoids backlash and play between moving parts and reduces the uncertainty of the reading.

There are different ways of adjusting the control point of the link in the segment slot so that the travel of the measuring element produces a 270° pointer rotation. One method, shown in Figure 1.88, is to slide a shoulder screw in the segment slot.

The link pivots on the shoulder screw. The position of the shoulder screw and the counter-weight determine the control point. The best location of the control point is found by repeated adjustment of the shoulder screw and counter-weight.

In a simpler design, the position of the control point is adjusted by bending a specially designed part of the segment. This design also requires repeated adjustment to find the optimum control point position.

1. Shoulder screw
2. Link
3. Toothed segment
4. Counter-weight
5. Washer
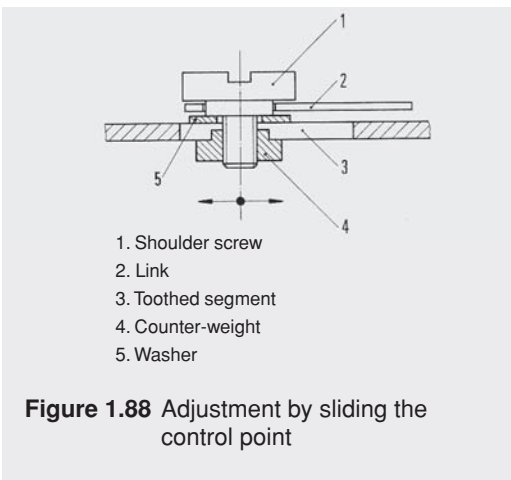
Figure 1.88 Adjustment by sliding the control point
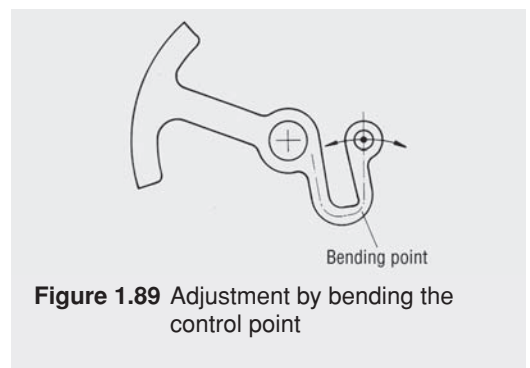
Bending point

Figure 1.89 Adjustment by bending the control point
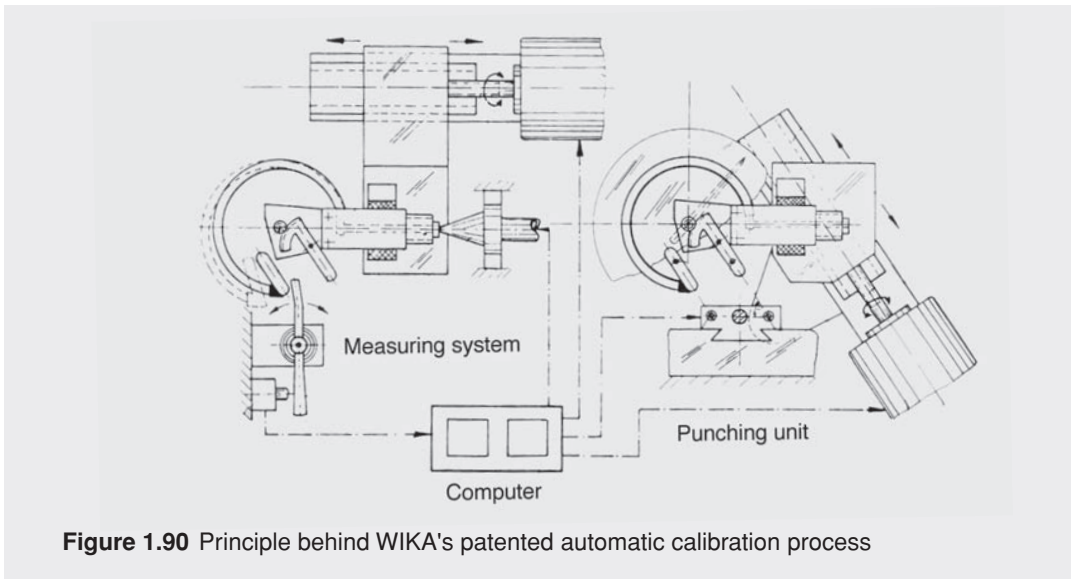
Figure 1.90 Principle behind WIKA's patented automatic calibration process

The number of repeated adjustments needed for both types of calibration greatly depends on the operator's skill. However, WIKA has developed and patented a new process that eliminates the need to adjust the control point by trial and error.

The individual travel of the measuring element is measured and input into a computer. The computer, using known mathematical relationships between the travel of the measuring element and the position of the control point, determines the optimum geometric location of the control point.

The control points are permanently stamped simultaneously on the endpiece of the measuring element and the segment. Then the link is permanently inserted between them using rivets. This automated calibration process can produce accuracies better than 0.5% . However, it requires considerable equipment investment and setup and is therefore economical only for large quantities.

The repeatability of instruments calibrated using this automated process is improved since the location of the control point is permanent whereas the control point of a traditional slotted link move-

ment may change due to vibration or a sudden external shock.

In cases where some adjustment of the control point is necessary after automated calibration, such as in gauges with the additional external force from electrical accessories, a specially designed rivet is used that allows manual recalibration.

Pressure readings can be affected by temperature. Since the temperature coefficient of the modulus of elasticity for the measuring element material is a known constant, the effects of temperature change can be compensated by making a temperature-dependent correction to the position of the control point using a bimetal strip.

Bimetal compensation is only effective if the temperature of the measuring element and the bimetal strip are the same. When this is not the case, such as with process fluid temperatures higher or lower than ambient, or with heat generation caused by pressure pulsations, alternate forms of temperature compensation should be discussed with the manufacturer.
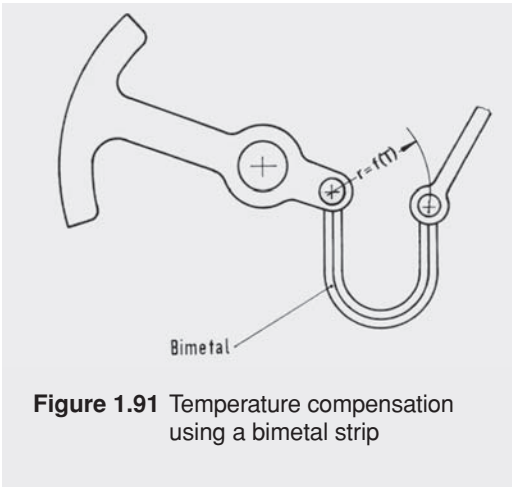
Figure 1.91 Temperature compensation using a bimetal strip

Besides just converting measuring element displacement to rotary motion, the gauge movement has other important functions. The varying cross-sections of measuring elements creates non-perfect linear displacements of the endpiece. The gauge movement converts these nonlinear displacements into an angle of rotation β. With a known location of the endpiece EP this angle can be adjusted by changing the length of the link.

A correct adjustment of the angle β compensates for the nonlinear travel of the measuring element. This is known as adjusting the linearity.

Figure 1.92 shows the **linearity** at various angles β at **p**/2 and the optimum setting for minimum nonlinearity.
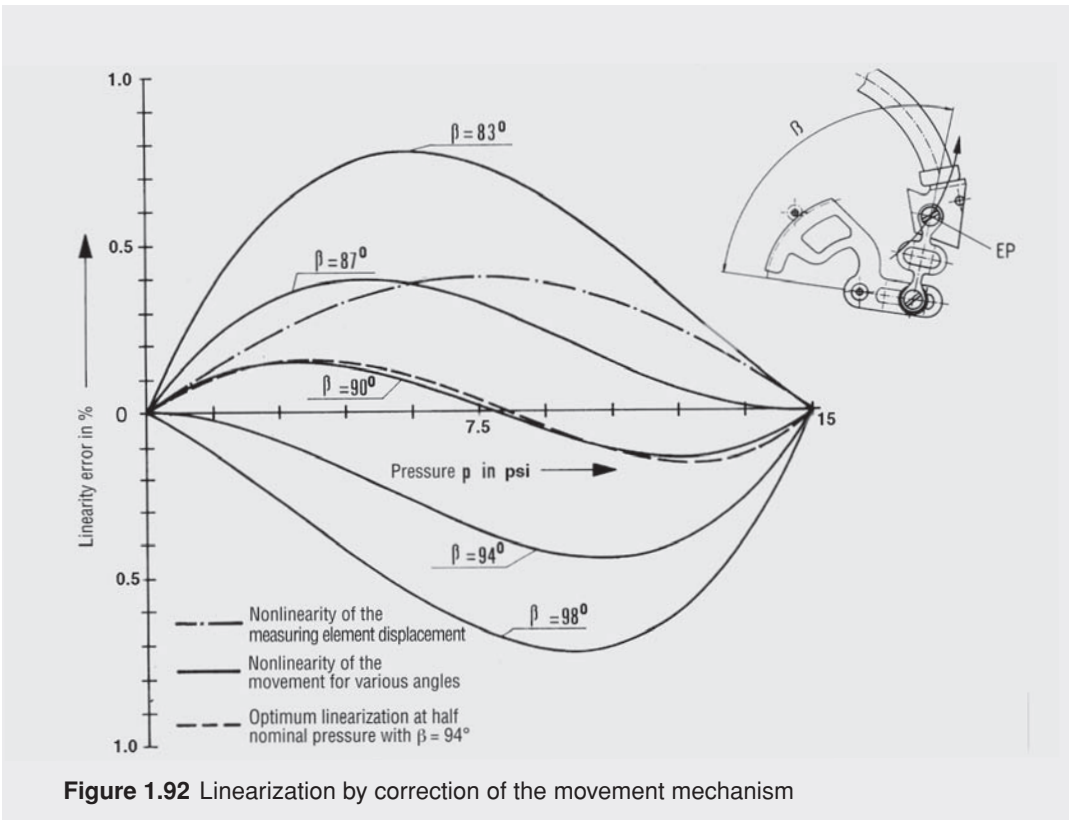
Figure 1.92 Linearization by correction of the movement mechanism

The remaining non-linearity can then only be compensated for by individually printing the dial graduations manually. This is done, for example, on instruments with high accuracies such as ±0.25% and ±0.1% of span.

Another condition for high reading accuracy is smooth, continuous pointer movement when subjected to a uniform change of pressure. This can be accomplished by using low-friction bearings, reducing play and using precise gearing. The quality of the moving parts and gears must meet tight tolerances. Special measuring equipment and processes have been developed at WIKA for this purpose.

Figure 1.93 shows a movement version with a zero correction. In this type of movement the gearing is mounted between platens that can be pivoted using a roller cam.

In movements damped with silicone oil, the pointer shaft and sometimes the toothed segment are damped by liquid friction, which is a function of velocity. The fact that this approach greatly increases the bearing forces acting on the contact areas of mating parts has restricted its use to just a few specific applications. (Refer to the description of pressure instrument cases in Section 1.4.4.)
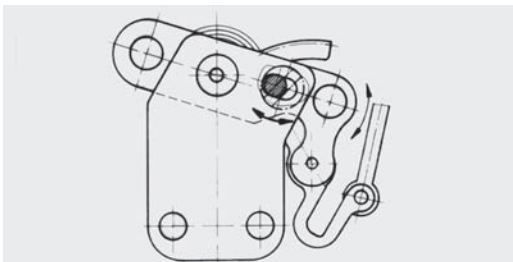
Figure 1.93 Zero correction of the movement by cam adjustment

Brass is preferred for platens and spacer columns; moving parts, such as the segment shaft and pointer shaft, are sometimes made of argentan.

If there is risk of corrosion, i.e. applications in chemical and petrochemical processes, all the parts are made of stainless steel. Special austenitic stainless steels are used for the moving parts.

Bearing bushings and segment gears made of polyacetal resin improve the travel characteristics. The combination of stainless steel and polyacetal resin is preferred for applications with a steady pointer position, i.e. with only occasional changes. This combination resists the sticking caused by contact corrosion in bushings and mating tooth flanks. However, the temperature resistance of the plastic is not sufficient for all applications.

In summary it can be said that the movement, in addition to its main function as converter of the measuring element displacement into an amplified angle of rotation, can also perform a number of important secondary functions such as **linearization**, **temperature compensation**, **damping of pointer movement** and **zero correction**. It is a sensitive component and needs to be protected against external damage.

1.4.3 Dials and pointers

In the last step of the signal path typical for pressure measuring instruments with a flexible measuring element, the pressure-proportional angle of rotation of the pointer shaft is indicated by a **pointer** and graduated **scale** on a **dial** to give the pressure reading. As for all other pressure measuring instruments, the pointer and dial must be designed to allow a reliable and clear reading. The fineness of the graduation and the thickness of the pointer edge are closely related. Precision measuring instruments are equipped with **mirrored** dials to eliminate **parallax reading errors**.

When the mirror image of the pointer edge coincides with the pointer edge itself, a true perpendicular angle of observation is assured for the reading. Figure 1.94 compares the pointers and graduations of instruments with ±1.5% and ±0.5% accuracies.
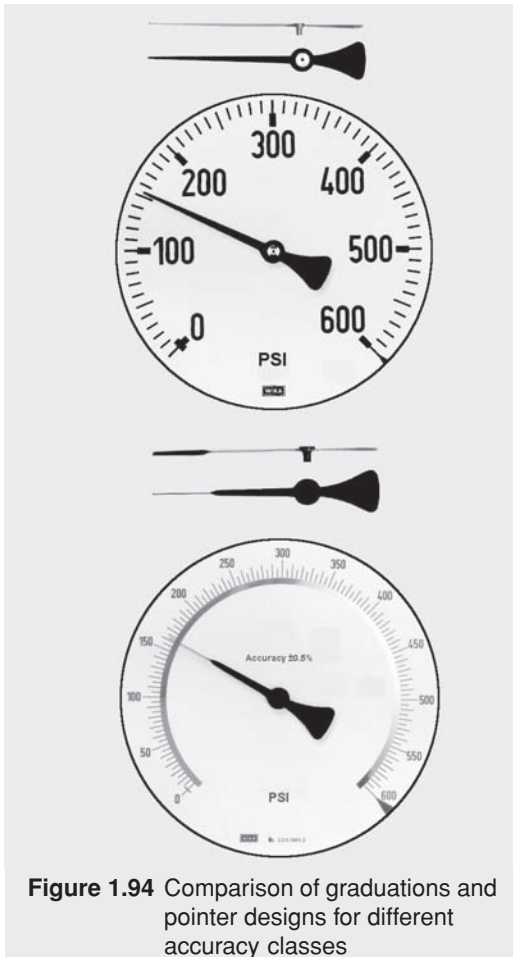
Figure 1.94 Comparison of graduations and pointer designs for different accuracy classes

Like the movement, the pointer and the dial can also be used for **zero correction**. To adjust the pointer, the **pointer bushing** remains firmly attached to the pointer shaft while the pointer arm is rotated on the bushing.

A simple design is sufficient if there are no pulsations. While the slotted pointer hub is held firmly with a screwdriver, the pointer arm is adjusted (Figure 1.95, right hand side).

The micro-adjustment pointer (Figure 1.95, left hand side) is much more sensitive. With the pointer mounted more firmly on the bushing, a miniature gear is used to transmit the adjusting force to the pointer arm.
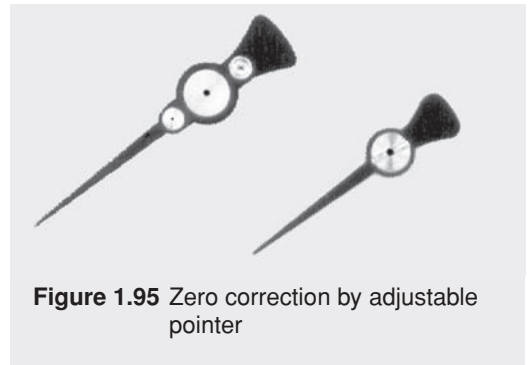
Figure 1.95 Zero correction by adjustable pointer

Precision instruments have delicate movements and adjustment of the pointer is not recommended. In such cases, a screwdriver or special key to obtain the desired correction can rotate the dial. Access is provided from the outside. A secondary graduation scale shows the amount by which the dial has been changed from the initial setting.

With all the zero correction methods explained here, it is important never to exceed the maximum load limits of the pressure measuring instrument. There are literally no limits to the design possibilities for the dial, i.e. the instrument's actual information medium. Once the technical requirements are met, attention can focus on design aspects, which in many cases will influence the entire appearance of the equipment accommodating the pressure measuring instrument. It is obvious that a medical instrument will require a different appearance than an instrument used in a chemical plant.

The information shown on the dial is specified in several standards for pressure measuring instruments with different grades of accuracy. Standard dial information for Bourdon tube pressure measuring instruments with accuracies from ±0.1% of span through ±5% of span are covered by ASME B40.1 - 1995 (Figure 1.96).
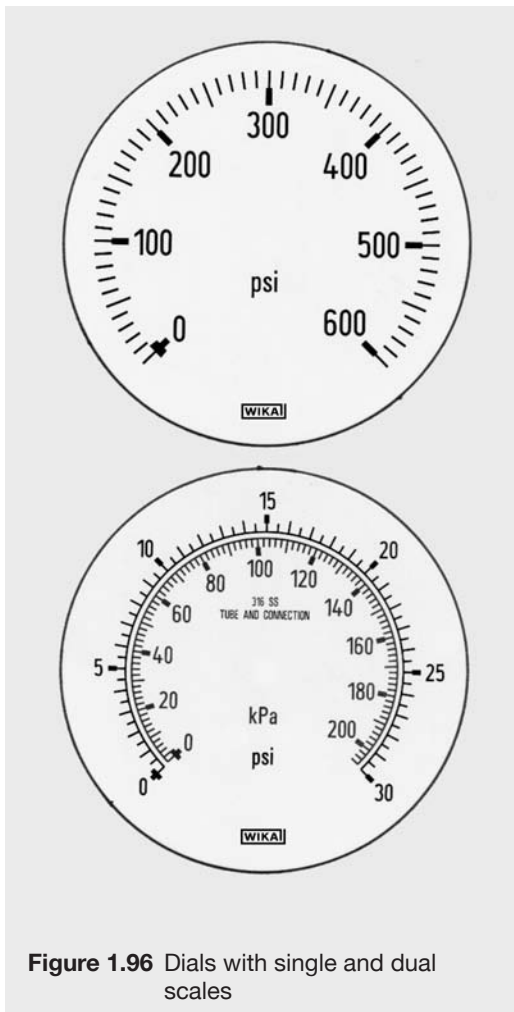
Figure 1.96 Dials with single and dual scales

1.4.4 The case

The main function of the case is to protect the functional elements needed to take the measurements, i.e. the measuring element itself, the movement and the pointer. The front of the instrument is covered by a **window**, which in many cases is held by a ring.

In addition to providing protection for the measuring system, the case has several other important functions such as mounting the instrument, assuring user protection in the event of leakage from the pressure-bearing parts, and allowing the instrument to be liquid filled in order to reduce wear and prolong life.

1.4.4.1 Connection positions

For high flexibility in the installation of a pressure measuring instrument, there are several possible positions for its connection. In "radial" connections, the connection can be moved into specific positions (such as 3 or 9 0'clock) as an option (Figure 1.97).
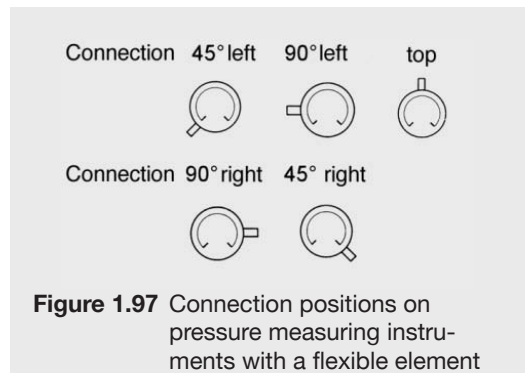
Figure 1.97 Connection positions on pressure measuring instruments with a flexible element

A rear connection, either in the center or off-center, is possible depending on the basic design of the instrument (Figure 1.98). Product data sheets show the different design options.

In some special applications, it may be necessary to install the pressure measuring instrument at an angle from the normal perpendicular position.

This special mounting position is indicated on the instrument dial by a position **sign**. Pressure measuring instruments are marked with this position sign only if they are designed to be installed at an angle of more than ± 5° from the normal vertical position.
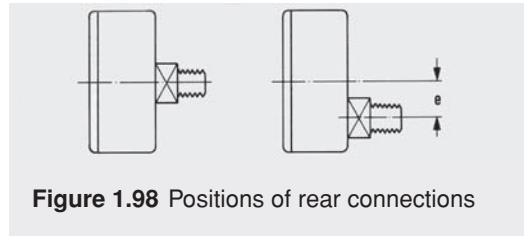
Figure 1.98 Positions of rear connections

Angle relative to the horizontal in clockwise direction	0°	30°	45°	60°	90°	120°	135°	180°
Meaning of position sign	Dial							
Position sign		30°	45°	60°		120°	135°	180°
Ordering code	NL 0	NL 30	NL 45	NL 60	none	NL 120	NL 135	NL 180

Figure 1.99 Mounting positions of pressure measuring instruments

1.4.4.2 Design types

Modular design of commercial pressure measuring instruments

In recent years there has been a trend toward modular systems in the interest of optimum and economical accommodation of the user's requirements. Figure 1.100 shows a modular system for standard pressure gauges in sizes $1^1/_2$" to 4", which do not require hermetically sealed cases. The simplest type of design is the impact-resistant plastic case with a snap-in window. This window can be easily removed for zero correction or for adjusting mark pointers. If an alternate window material such as glass is required, a **friction ring** is used. A **profile ring** with a u-clamp mounting bracket and a **front flange** are used to install the instrument in a control panel. The profile ring and u-clamp bracket need a panel hole with the same diameter as the case. With a front flange, on the other hand, threaded bolts hold the gauge in the control panel. A rear connection is the best choice in both cases.

The **rear flange** is used together with the **lower mount connection** for wall-mounting purposes. The flange, which is attached to the instrument case, is then held directly in place by three screws. The materials used in this modular system are plastics (ABS), steel, stainless steel and brass.

1. Back connection
2. Socket
3. Measuring element
4. Endpiece
5. Restrictor
6. Bottom connection
7. Socket
8. Movement
9. Dial
10. Pointer
11. Mark pointer
12. Stop pin
13. Case
14. Window
15. Friction ring
16. Front flange
17. Profile ring
18. Rear flange
19. U-clamp mounting bracket
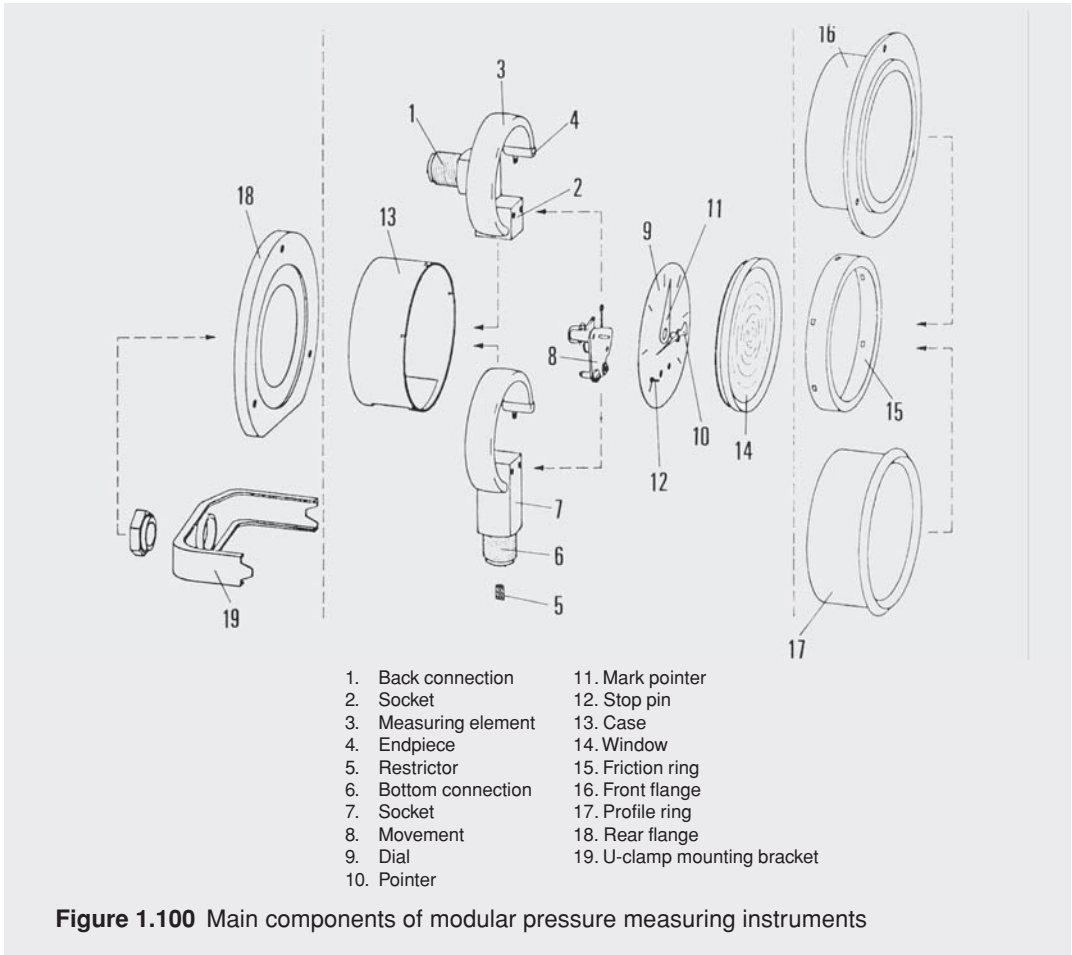
Figure 1.100 Main components of modular pressure measuring instruments

An number of aesthetic surface finishes (i.e. chrome-plated, nickel-plated, or painted with special colors) are available to meet various customer requirements. High quality, oven-baked enamels, applied by automatic painting machines, give even steel cases a high degree of corrosion resistance.

Modular design for industrial measuring instruments

The WIKA modular system for industrial pressure measuring instruments used in mechanical engineering and process technology meets high requirements with regards to ruggedness and construction. **A bayonet ring** not only allows the instrument to be opened and closed with ease, its special shape also adds exceptional strength to the case. The various mounting options previously described are also possible for industrial instruments.

1. Case
2. Gasket
3. Bayonet ring
4. Window

Figure 1.101 Modular system for industrial pressure measuring instruments with bayonet ring

While the recessed edge of the case provides a good sealing surface, the smooth exterior prevents dust accumulation and its corrosive consequences.

Forged cases for liquid filling

In addition to brass or aluminum cases with a threaded ring, which are now rarely used, a case design that has gained wide popularity is the hot-forged brass case with a crimped ring.

The case and connection form one unit. With the window held in place by a crimped ring, the instrument has exceptional strength (Figure 1.102).

A **cover ring** is added for cosmetic purposes, but a profile ring or front flange for panel mounting can replace it. Having very few sealed joints, this design is ideal for a liquid filling. It has proven itself many times over under the harshest conditions found in fluid power service and other hydraulic applications.

1. Forged brass case
2. Crimped ring
3. Cover ring
4. Gasket
5. Window

Figure 1.102 Forged brass case for liquid filling
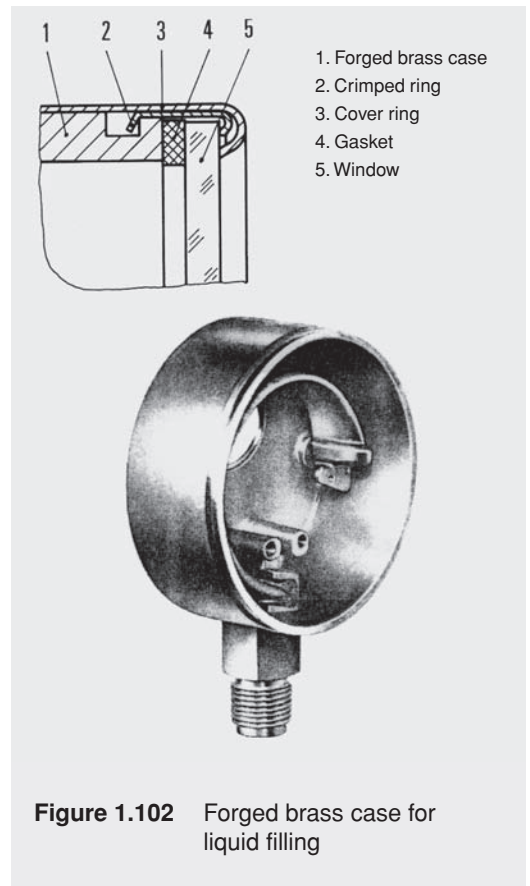
1.4.4.3 Vibration damping by liquid filling

Many pressure measuring instruments are exposed to vibrations or shocks, transmitted either by the process fluid itself, by the instrument mounting or during operation. As a result, the moving parts and the pointer start to vibrate and pressure reading becomes very difficult or even impossible. In extreme cases the measuring element may be broken by the resonance and hazards may occur from leaking fluid. The problem and its general solution are given special consideration below for Bourdon tube measuring systems.

Resonant frequencies and amplitudes

The resonant frequencies of measuring elements with various pressure ranges and their amplitudes in the resonant state were determined on an electro-hydraulic oscillator. Figure 1.103 shows the average resonant frequencies as a function of the full scale pressure range. The resonant frequencies of the various measuring elements rise with the full scale pressure. Excitation with their resonant frequencies produces the average amplitudes shown in Figure 1.104 for the various full scale pressure ranges. Displacement values under full scale pressure are also shown for comparison.

Figure 1.104 Empirically derived amplitudes of measuring elements excited with resonant frequency

The resonant resistance of the measuring elements was also investigated. The results are summarized in the following section. The oscillator's acceleration was raised from 25 m s^{-2} to 50 m s^{-2} at a full scale pressure of 200 PSI and higher.

When the measuring elements are subjected to their respective full scale pressure, there is approximately a 50% reduction of amplitude. The arching of the tube profile caused by the internal pressure gives the circular Bourdon tube a higher moment of inertia. This results not only in a reduction of amplitude but also in a slight rise (less than 1 Hz) of the resonant frequency. If the oscillator frequency is adjusted to the modified resonant frequency, the amplitude will rise again to approximately 80% of the original value. The reverse effect of vacuum can occur on a 15 PSI gauge.

Figure 1.103 Empirically derived resonant frequencies of the measuring elements

Resistance to resonance

A measuring element's resonant resistance is a special case of vibro-stability, i.e. the number of oscillating cycles in resonance after which the measuring element suffers damage. To determine a measuring element's resistance to resonance, it is subjected to 50% of its nominal pressure and excited with its resonant frequency. A pressure drop in the measuring element indicates that the circular Bourdon tube has cracked. Figure 1.105 shows the average number of oscillating cycles up to breakage of the Bourdon tubes. Differences in the resonant resistance of the various measuring elements are due to differences in the geometry of their tubes.

All the parameters with an effect on the elastic modulus of the Bourdon tube will also change the system's resonant resistance. These parameters are the wall thickness **S**, the coil height **2b** and the coil width **2a** of the tube (see Figure 1.64). The higher pressure ranges display far better resistance to resonance than pressure ranges less than 160 PSI.

In 200 PSI systems the amplitude at an acceleration of 25 ms^2 already drops to a value that is smaller than the displacement at nominal pressure (Figure 1.104). This results in a higher level of resonant resistance with high numbers of oscillating cycles up to the onset of damage. Therefore the acceleration has to be raised to 50 m s^2. Further interesting aspects of these investigations are the points of damage on the measuring element. Generally there are only two possible areas where the Bourdon tube can be broken by mechanical vibrations. Either notching produces a crack in the weld joining the tube to its support or the tube breaks at the most heavily loaded point of its top edge (see Figure 1.57). On measuring elements with a flat cross-section, the weld seam cracks. Superimposition of internal pressure exerts an additional load on the top edge; in this case the Bourdon tube cracks on its top edge.

In a further test, various types of measuring elements were examined as to their resonant resistance under identical nominal pressure (200 PSI). Table 1 shows the various types, their resonant resistance and the applied acceleration.

Measuring element type	Acceleration [m/s^2]	Resonant resistance
a) flat (b/a = 0,30)	25	30 000
b) flat, tube inserted 7 mm in tube support	25	30 000
c) high (b/a = 0,52)	25	100 000
d) flat , under Nominal pressure	25	100 000
e) flat , liquid filling, oil (25 mm^2/s)	100	1 200 000
f) flat, in liquid filling, glycerine/water (120 mm^2/s)	100	no break (>10^7)

Table 1.1 Resonant resistance and applied acceleration

As the table shows, there is no difference in resonant resistance between types a) and b). Unlike measuring systems a), the tube in b) was inserted a depth of 7 mm in the tube support prior to welding. With soldered measuring elements this is essential in order to produce a durable joint, but with welded parts it brings no improvement.

A change of tube geometry in the height/width ratio (b/a) for category c) in Table 1.1 prolongs life under conditions of resonance by a factor of 3. The same applies to pressurization of the specimen. In this case the reason for the better resistance to resonance lies in the reduction of amplitude. The best results are obtained when the Bourdon tube is damped with a liquid filling. The resonant resistance is improved by a multiple compared to undamped versions when using oil with a viscosity of just 25 mm^{2}s^{-1}. To obtain a resonance-induced fracture in category e), the load had to be applied at an acceleration rate of

100 ms^{-2}. Category f) confirms that a resonance-induced fracture no longer arises in a glycerine-water mixture of just 86.5/13.5% (viscosity 120 mm^2 s^{-1}) when exposed to severe mechanical vibrations.

Investigation of various instrument types

To investigate complete measurement instruments it is necessary to perform tests of even greater complexity than those for the measuring elements. An instrument's movement is an independent component that is just as liable to vibrate as the measuring element. The two components are joined together by the pull rod. To assess vibrostability, four instruments with different types of damping were subjected to a vibration test. In addition to an undamped instrument there was one instrument with pointer shaft damping, one with pointer shaft and segment lever damping, and one with liquid filling. The results of these tests are summarized in Table 1.2.

Relatively high pointer amplitudes arise at nearly all frequencies in the vibration test on an unfilled instrument with an undamped movement. The instrument's vibration characteristics are affected by play in the gearing and at the pull rod in addition to vibrations in the measuring element. There is no longer any one clearly defined resonance frequency but whole frequency ranges in which the pointer vibrates with a lesser or greater amplitude. The frequencies with the maximum pointer amplitudes are determined by running through this frequency band (Figure 1.106). Since there are no major damping forces, the undamped instrument proves to be durable in the vibration fatigue test. After a test period of 200 hours the zero deviation amounted to only 3%, and all the components were still in working order. On undamped instruments the tube can vibrate with a large amplitude; hence there is a risk of resonance-induced fracture on the measuring element with loss of pressure medium.

Damping features	Zero-deviation after 50/200 hours	Condition of the instruments after 200 hours
No damping	2,3/3,0 %	functional with limitations
Pointer shaft with damping	2,3/66 %	no longer functional
Pointer shaft and segment lever axis with damping	3,9/34 %	no longer functional
Liquid filling with glycerine/water (120 mm^2/s)	0,6/0,8 %	still fully functional

Table 1.2 Results of tests on various damping methods

With a damped movement, an extension of the pointer shaft or segment lever axis runs in a small pot filled with a high-viscosity medium that generates the desired damping forces. Unlike unfilled instruments with an undamped movement, the indicator on instruments with a damped movement is affected by virtually no vibrations at all. Even the tube vibrations are kept within limits via the pull rod. At first glance this would appear to be a very good solution for instruments at measuring points exposed to mechanical vibrations. Practical tests show that the opposite is the case.

Damping the movement means it is necessary to transmit all the damping forces from the gear, the segment lever and the pull rod up to the end of the tube. The forces entailed are high and cause these components to wear severely. Under the above mentioned test conditions, the instrument was unusable after just 100 hours. The segment toothing was damaged and the bearing pins were worn away, causing the toothed segment to detach and tilt inside the movement. Damping of the measuring element was no longer assured and the tube vibrated without restriction.

Similar damage was also discovered on the instruments with a damped pointer shaft and segment lever axis. Here, too, the forces of the circular Bourdon tube had to be absorbed by the movement in conditions of mechanical vibration. The two dampers and a PTFE gear were able to prevent damage to the measuring system temporarily. After a test period of 200 hours, the instrument had a zero deviation of over 30% (in the unpressurized state pointer at 50 PSI). The main reason for this was a worn out pull rod.

Although the greatest pointer amplitude of an undamped 160 PSI instrument lies in the region of 43 Hz (see Figure 1.106), this is not the critical frequency for the same instrument with a damped measuring system. For an instrument of this type the greatest damage occurs at the resonant frequency of the measuring element. At this frequency the measuring element tries to vibrate with excessive amplitude against the damped mechanism, producing a loud rattling noise.
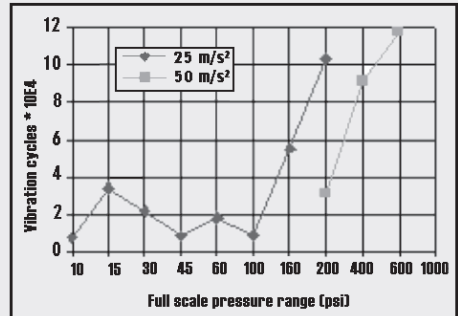
Figure 1.105 Resonant resistance, number of vibration cycles up to resonance-induced breakage
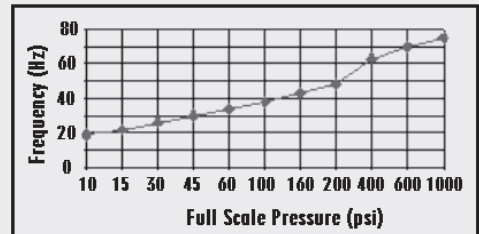
Figure 1.106 Frequencies with maximum pointer amplitude of unfilled instruments without a damped movement

This is a clear sign of high wear on the transmitting components.

In liquid-filled instruments, there is damping of vibrations on the measuring element as well as in the movement and on the pointer. Good damping of the measuring element prevents large amplitudes and forces, safeguarding the instruments against breakdown. In addition to its damping properties the liquid filling also acts as a lubricant and coolant for all the moving parts, helping therefore to reduce wear further still. The liquid-filled instrument was still in full working order after the vibration fatigue test. This was the only instrument where the zero deviation after the test did not exceed the 1.0% accuracy limit for the class.

1 Pressure measurement

The **damping** of vibrations is effected by the velocity-dependent friction of the moving parts in the liquid. With fast changes the average value of the pressure is shown as the effective value, with slow changes there is no corruption of the value.
Friction inside a liquid depends on the viscosity of the liquid as well as on the velocity of the moving parts. Since the viscosity of liquids is conditional on temperature, a choice of standard fillings is available to match the various thermal conditions of application. Figure 1.107 shows the relationship between temperature and the viscosity of the standard fillings.

When electrical accessories are installed, insulating oils are used to ensure the necessary insulation resistance. Inert liquids are used if there is a risk of chemical reaction between the measuring fluid and the filling liquid in the event of a leak, i.e. oxygen with glycerine.

The low temperature dependence displayed by silicone oils compared with other liquids is proven in extreme climatic conditions such as exist in Siberia or Alaska. Potential icing up of the moving parts is prevented by the liquid filling, i.e. the instruments are functional even in extreme conditions.

A further advantage of liquid fillings is that they rule out corrosive attack on the interior of the pressure measuring instrument.

Figure 1.107 The kinematic viscosity of various filling liquids as a function of temperature
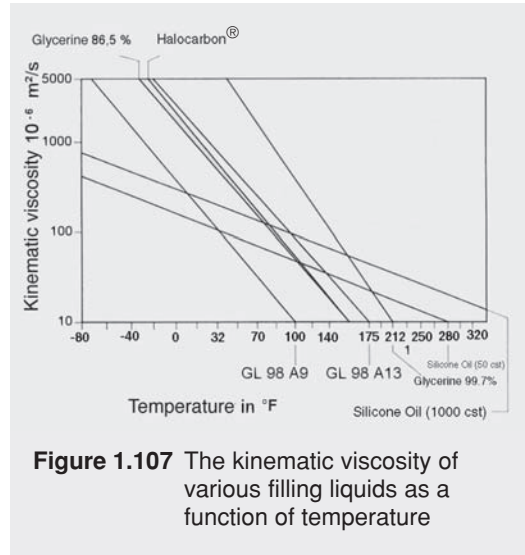
Pressure gauges with a flexible element need contact with the surrounding atmosphere for reference purposes. Liquid-filled instruments must be closed for transportation, but must be vented when put into operation and then remain vented.

This means that hermetically sealed instruments need design features that prevent pressure build-up due to thermal changes.

There are two primary ways to reduce case pressure buildup in hermetically-sealed, liquid filled instruments. The first is to clamp or bond a diaphragm, or **pressure compensating membrane** to the inside back of the gauge case (Figure 1.109). A second option is to mount a transparent film membrane underneath the window. This option is called a **membrane window**. In both cases one side of the membrane is vented to the atmosphere which allows the volume of the case to increase or decrease with insignificant changes in case pressure.
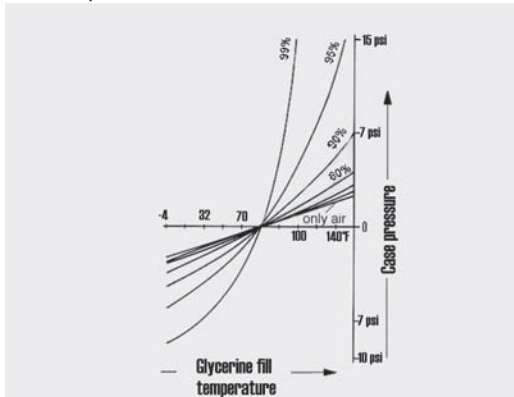
Figure 1.108 Case pressure buildup for liquid filled gauges without temperature compensation

1. Case
2. Blowout back
3. Pressure-compensating membrane
4. Vent hole to the atmosphere
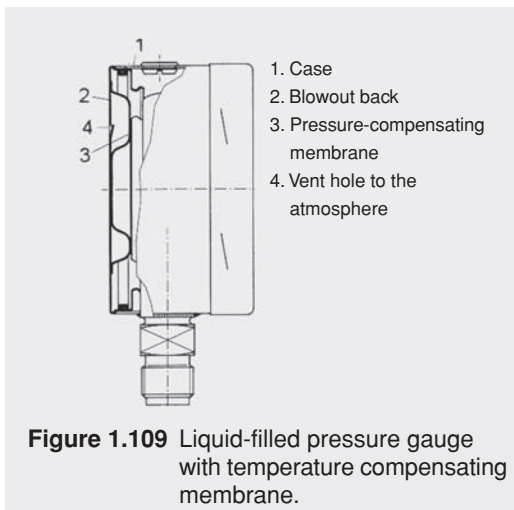
Figure 1.109 Liquid-filled pressure gauge with temperature compensating membrane.

Internal pressure compensation eliminates the need for an air bubble which is particularly important for applications where the gauge is used in an inclined position and the bubble interferes with the reading.

Summary

The liquid filling:
- extends the life of the gauge when used in high-dynamic operating conditions
- prevents resonance-induced fracturing of the Bourdon tubes
- allows readings even when vibration and pulsations are present
- prevents aggressive ambient air from entering the gauge case
- prevents condensation and the formation of ice
- improves overall operational reliability even under extreme loads
- is an economical solution to pressure measuring problems.

1.4.4.4 Safety of pressure measuring instruments

The service life of pressure measuring instruments can be improved considerably by using a liquid fill to dampen vibration and by using corrosion-resistant austenitic steels for the wetted parts. Even with these protections, failure due to aging of the pressure system will eventually occur. Safety factors must be considered, therefore, to protect the operator in the event of a failure.

Protection from solid front cases

One potential hazard for the user is leakage of the process fluid, which may be hot, toxic or corrosive, from a measuring instrument, process pipe or tank.

Another risk is the energy stored in the Bourdon tube, which in the event of damage may be released with an extremely high velocity. This type of damage can occur from aging cracks in the tube or from faults in either the material or its joints. Even the most stringent production methods and quality control programs cannot completely eliminate this possibility. The following example shows the magnitude of the energy stored in a Bourdon tube at its full scale pressure.

For liquid process fluids:

$$W_{Liq} = \frac{\chi \cdot V_N}{2} \cdot p_N^2 \qquad (1\text{-}39)$$

and for gaseous fluids:

$$W_{Gas} = p_N \cdot V_N \cdot \ln \frac{p_{amb}}{p_N} \qquad (1\text{-}40)$$

W = Energy

χ = Compressibility of the liquid

$(\chi_{water} = 44 \cdot 10^{-6} \frac{m^2}{N})$

V_N = Volume of the measuring element at full scale pressure

p_N = Full scale pressure of the instrument

p_{amb} = Atmospheric pressure

Figure 1.110 shows the energy for a series of three Bourdon tube instruments. The sudden jump in the characteristic curves results from the switch from C-shape Bourdon tubes for small and medium full scale pressures to helical Bourdon tubes for high and extremely high pressures, and from the corresponding change of volume. The energy analysis for liquid process fluids does not take into account the gases dissolved in them. Depending on the actual gas content, the energy level will be lie somewhere between the curves for gaseous and liquid media.

Comparison with the energy of a bullet gives a more vivid idea of just how much energy is represented by the curves. For a bullet with a mass of

5 g and initial velocity of 500 m/s the energy figure works out at approximately 63 000 Ncm (Figure 1.110).

Figure 1.110 Energy stored in a Bourdon tube at full scale pressure with liquid or gaseous process fluid

In the event of damage, the energy stored in the Bourdon tube is released with various time frames. With small leaks at the joints or hair line cracks in the Bourdon tube, the pressure inside the case will rise. With standard pressure gauges, this increased pressure may then escape to the atmosphere through leaks in the case without rupturing the case or window. With liquid-filled gauges, however, the pressure rises far more quickly because of the incompressibility of the fluid. The burst pressure limit for a laminated safety glass window (typically 0.16 inches thick) is approximately

70 to 90 PSI for 2^1/$_2$" gauge sizes
45 to 60 PSI for 4" gauge sizes
20 to 45 PSI for 6" gauge sizes

provided the window is not weakened by holes. Experience shows that a slow pressure buildup in the case is not typical in the event of damage to the Bourdon tube or its connection. Gauges with Bourdon tubes nearing the end of their functional life have been known to burst suddenly when pressurized.

The quickness with which this happens eliminates the possibility of a slow leak from the case or window. The window and parts of the measuring system are catapulted into the air, putting any personnel in front of the instrument in great danger. It is known that glass splinters with a kinetic energy far less than that of a bullet can cause serious facial injury and loss of vision.

To reduce the possibility of harm to the operator in the event of a measuring system failure, WIKA offers solid-front safety cases. These cases have been designed to meet European safety standards which are far more stringent than those in the U.S. These European standards (as outlined in EN 837) require that if a volume equal to the volume of the Bourdon tube is pressurized to 2.5 times the full scale pressure and suddenly released inside the case, the user is guaranteed of the following:

1. The separating wall between the dial and the Bourdon tube will not rupture.

2. The pressure will blow out the back plate and vent through the rear of the gauge.

3. The Bourdon tube is made of a material that will not splinter if ruptured.

4. The laminated safety glass window will not shatter or splinter

The design of the solid-front safety case can be seen in Figure 1.111.

1. Blow-out back plate
2. Pressure-compensating membrane (optional)
3. Non-splintering Bourdon tube
4. Unbreakable separating wall
5. Laminated safety glass

Figure 1.111 WIKA solid front safety gauge design
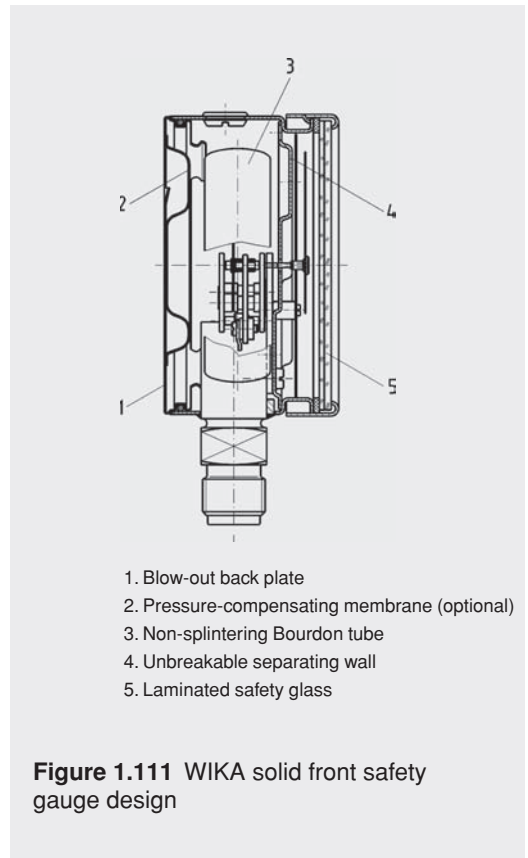
A variety of pressure gauges with the WIKA safety case design are available as:

- pressure measuring instruments in $2\frac{1}{2}$", 4" and 6" sizes for all standard pressure ranges from 10 to 60,000 PSI, with and without liquid filling

- pressure measuring instruments with electrical accessories such as inductive proximity sensors in intrinsically safe control circuits and remote transmitters in 4" and 6" sizes.

Gauges in a 6" size are commonly used for adding electrical accessories. They have a higher level of accuracy and reliability because of their high control forces from the larger Bourdon tube element.

For applications in the chemical and petrochemical industries, solid front instruments are recommended. Solid front instruments meet the demand for reliability, long life and safety because they are designed with corrosion resistant Bourdon tube materials and cases, and they are typically liquid filled.

Standards in many countries outline safety requirements for Bourdon tube pressure gauges. In the U.S., Underwriter's Laboratories has approved gauge designs for the welding and medical industries. U.L. bases their approval on the results of actual tests in their laboratories to insure the gauges meet the stringent demands. In Canada, CSA performs the same type of testing and approvals.

Safety case gauges in 4" or smaller sizes can be supplied without the baffle wall between the pressure system and the dial. In this case, special venting either through blow out plugs or through openings in the bottom of the case must be used. In addition, the window must be held firmly in place by a retaining ring to prevent it from blowing off in the event of a tube rupture.

Summary
The case is an important component of the pressure gauge because:
- It protects the pressure system from outside influences to ensure accurate readings
- It helps to extend the instrument's life by allowing the gauge to be liquid filled
- protects the user in the event of a pressure system leak

Pressure gauge accessories are an important part of pressure measuring systems since they are needed for additional monitoring and control functions. Some of these accessories are described in the following section.

1.4.5 Electrical and pneumatic accessories

Pressure gauges can be equipped with electrical or pneumatic accessories such as alarm contacts or transmitters. These accessories convert the pointer rotation or the rotation of the pointer shaft into an electrical or pneumatic output.

1.4.5.1 Alarm Contacts

Alarm contacts can be divided into two separate types; direct or indirect.

Direct contacts

Direct contacts are simple mechanical switches which open or close an electric circuit with a contact arm attached to the pointer. The simplest form of direct contacts is called the **sliding alarm contact**.
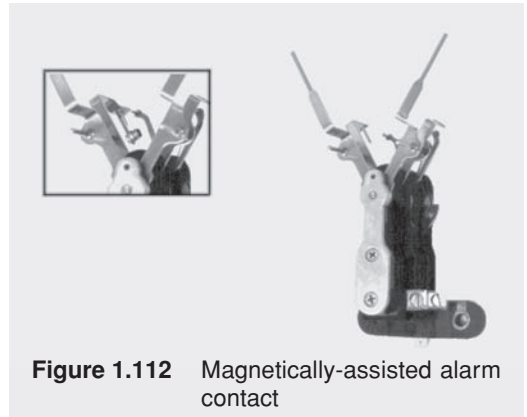
Figure 1.112   Magnetically-assisted alarm contact

The "open" and "close" is made at two contact pins. Due to the voltage difference, an electrical arc is generated during switching. This arc burns the contact material and shortens the life of the switch.

To reduce the electrical arcing, a small permanent magnet can be put under the contact pin of the control arm which attracts the other contact pin with a "snap" right as the control point is reached. The same holds true when the pointer moves away from the control point. The magnet keeps

the contact arm attached to the contact pin until the pressure overcomes their magnetic attraction with a "snap". Alarm contacts with this magnet are called **magnetically-assisted alarm contacts**.

Magnetically-assisted alarm contacts have several advantages over sliding alarm contacts. They have a higher switching capacity, a longer service life, and are more vibration resistant. Magnetically assisted alarm contacts can also be used in liquid filled gauges, whereas the arcing from sliding alarm contacts makes them inappropriate for liquid filled gauges.

The disadvantages of magnetically assisted alarm contacts are their higher switching hysteresis between upscale and downscale movement and the error of indication it causes. For this reason, magnetically-assisted alarm contacts should not be used in precision measuring instruments.

The operation of both sliding and magnetically assisted alarm contacts is affected by the ambient atmosphere as well as by the electrical current. Therefore, the contact materials are almost always precious metals, precious metal alloys or sintered materials containing precious metals, since they all have good oxidation resistance and excellent electrical conductivity. When working with low voltages, such as in potentially explosive areas, the chemical resistance of the contact materials is important since their corrosion leads to increased contact resistance.

The standard contact material is a sintered alloy with 30% tungsten and 70% silver. It has good characteristics at high and low voltages and has good arcing resistance. Gold contacts have a good oxidation resistance and conductivity. They are used for low-voltage switching down to the millivolt range.

Platinum alloys, such as platinum iridium, display very high levels of hardness and wear resistance combined with good chemical resistance. They are used for extreme conditions, especially for low-voltage applications. In addition to the materials listed above, other precious metals or alloys are available for special applications.

Multiple contacts can be installed into one pressure gauge, with common or independent connections. The maximum number of contacts for each instrument depends on the pointer drive (torque) of the pressure system which must compensate for the negative effect on the accuracy. Gauges measuring lower pressures generally have a smaller pointer drive than gauges measuring high pressures and therefore can support fewer alarm contacts.

For instruments will low pointer drive, such as those with full scale ranges of 100PSI and lower, the counter force of the contact arm against the pointer can be large enough for the contacts to shift the position of the pointer and therefore change the accuracy. Since these counter forces can be additive or subtractive depending on the direction of the force, they cannot be compensated for during calibration.

A **contact protection relay** can be connected to the contacts to increase their life span. The control circuit of this relay, which has a much higher switching capacity on the output side, loads the contact - in some cases by duty cycle - with low switching power.

Other direct contact designs include micro-switches and reed switches.

Micro-switches are toggle switches, which in most cases are installed directly into special movements. They are vibration resistant and have a higher switching capacity than sliding or magnetically-assisted contacts. However, the disadvantage of micro-switches is that they have relatively high actuating forces which create a higher switching error.

Reed switches consist of two contact plates in an evacuated glass tube. They are attracted when a permanent magnet carried by the movement passes them. They have very small dimensions.

Indirect contacts

Indirect contacts require an external power source and an amplifier circuit, in addition to the components installed in the instrument. Indirect contacts can be electric or pneumatic.

Inductive contacts

Electric inductive proximity switches conform as a rule with NAMUR specifications. Most of these switches have a slotted design and are therefore commonly called **slot initiators**.

They are made of a pair of axially opposed coils separated by an air gap (slot). This pair of coils is excited by a high frequency transistorized oscillator. The electromagnetic field is concentrated in the air gap between the coils. When a metallic control flag enters the air gap, the coil system is attenuated and the internal resistance of the initiator increases. When the control flag leaves the air gap, the opposite occurs. This change of resistance controls a switching amplifier and the units connected to it.

1 Oscillator transistor
2 Filter capacitor
3 Coils
4 Electromagnetic field (in the slot)

Figure 1.113   Circuit diagram of a typical slot initiator
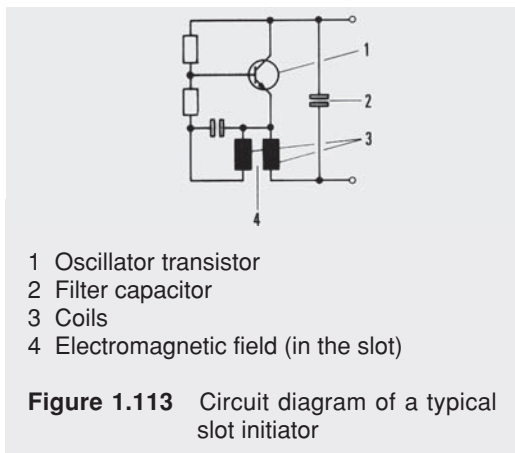
The initiator takes the place of the contact pin in the measuring instrument, but is controlled by the instrument pointer in the same way.

Since the switching takes place without mechanical contact, the electrical system experiences virtually no wear. The effect on the mechanical system is small. Since the output values meet most standards, the inductive contact can be used for many applications. Control units with a direct current power supply, a switching amplifier and output relays, i.e. all the essential supply and output units, are available as separate units.

A Pressure measuring   1 Power supply
   instrument   2 Supply voltage
B Power supply   3 Control circuit
C Amplifier
D Load, i.e. output relay

Figure 1.114   Circuit diagram of a pressure measuring instrument with an inductive contact, power supply and output units
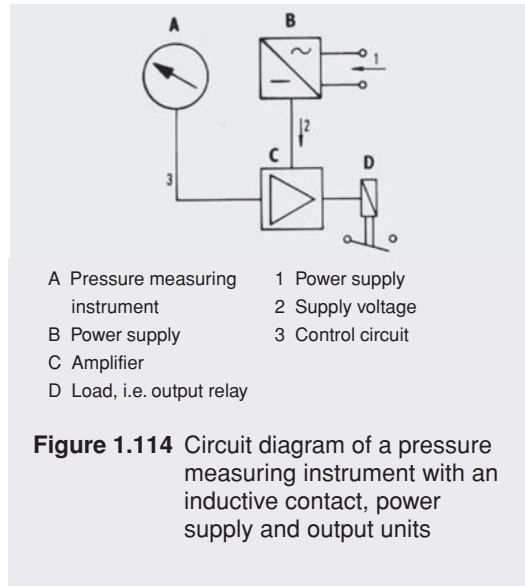
The amount of energy supplied by the initiator is small enough to allow safe operation in a Zone 1 explosive atmosphere as long as intrinsically safe circuits are used in the separate power supply unit.
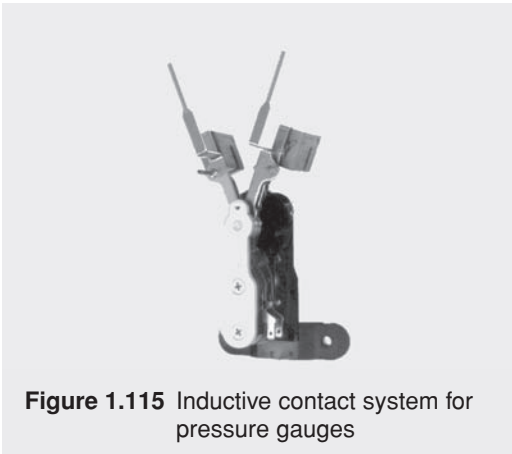
Figure 1.115 Inductive contact system for pressure gauges

These advantages explain why the inductive contact has become popular in a wide range of applications. Today it is used wherever reliable switching, long life, high accuracy and explosion protection are very important.
Several initiators can be installed in one pressure gauge. They can also operate in a liquid filled gauge.
Other indirect contacts are capacitive proximity switches and opti-electronic switches. They are rarely used, however, in pressure gauges.

Pneumatic contacts

In addition to the electrical contacts described above, there are pneumatically controlled systems. They are preferred for applications with explosion hazards.

Externally, the contacts looks similar to the inductive contacts. The control head (instead of the slot initiator) is carried by the control arm, the cables are replaced by air lines and the downstream electrical amplifier by a low-pressure switch.

Pneumatic contacts are rarely used now and therefore will not be described here.

1.4.5.2 Transmitters

Transmitters differ from contacts in that they provide a continuous signal proportional to the measured pressure. This signal can be used for indicating, recording, monitoring, controlling or remote transmission purposes.

Potentiometric transmitter

The simplest transmitter design is the **potentiometric transmitter**. This transmitter can be installed inside the case or on the back of the instrument. It is made up of a resistance wire wound on a circular support and a wiper arm joined to the pointer shaft. The resistance winding and wiper arm are generally made of a precious metal alloy with high corrosion resistance and a low temperature coefficient.

The potentiometric transmitter is a voltage divider. The resistance between the start of the winding and the wiper arm changes as a function of the pointer position, and the partial voltage between these two terminals changes accordingly.

In addition to linear standard windings, numerous special designs are available, such as function windings, short-circuit bars at any desired position, additional taps, separations etc. Several potentiometers with independent windings can be combined. For explosion protection the potentiometric transmitter is installed in a pressure-proof case which makes it suitable for use in a Zone 1 potentially explosive atmosphere.

Capacitive transmitters

The capacitive transmitter has become even more popular than the potentiometric transmitter. Its main advantages compared to the potentiometer are: no mechanical contact and therefore practically no wear, high sensitivity, and a load-independent continuous, current signal output.

Capacitive transmitters consist of a **differential capacitor** with a rotor and a measuring bridge with series-connected amplifier. The rotor is joined to the pointer shaft of the measuring instrument. Rotation of the pointer unbalances the bridge, which changes the voltage at the amplifier input. The output signal is a direct current signal, generally 0 or 4 to 20 mA. The current is load-independent. This means that below the specified load limit any resistance changes, i.e. temperature-related changes of the line resistance, have no effect on the signal.

Special designs with optional features are available, i.e. a signal output of 0 to 5 or 10 mA, galvanic separation between supply and output circuits, an integrated power pack for direct connection to an alternating voltage, and intrinsic safety designs. This means that they can be operated safely in a Zone 1 potentially explosive atmosphere with an adequate power supply .

Both transmitter types share a common disadvantage. Since they are joined to the pointer movement, any movement errors, such as due to friction or wear, will affect the electrical signal.

Pressure gauges with a Hall effect sensor, however, avoid this problem because they are not in direct contact with the gauge movement and the electrical signal is determined by changes in magnetism. (see Section 1.3.2.2).

Pressure measuring instruments, mechanical, with diaphragms or capsules, for gauge pressure, absolute pressure and differential pressure

WIKA®

1.4.6 Special flexible element pressure measuring instruments

1.4.6.1 Pressure measuring instruments for absolute and differential pressure

As outlined in Section 1.2, gauge pressure, vacuum, absolute pressure and differential pressure differ only in their reference point. Therefore the measuring principles and elements described in detail in the previous sections can all be used for the measurement and indication of all of these various types of pressure, as long as the measured pressure is compared with the appropriate reference pressure. To do this, the reference pressure must surround the element of the pressure measuring instrument or fill the element.

The simplest pressure measurement is "gauge" pressure which uses atmospheric pressure as the reference. As previously described, the measured media enters the inside of the measuring element, which is surrounded by the atmospheric pressure. The difference between the media pressure and the atmospheric pressure (whether positive pressure or vacuum) is then indicated on the dial.

To measure differential or absolute pressure, two closed measuring chambers are needed that are separated by the measuring element.

Figure 1.116 Typical chamber system for differential or absolute pressure measurement

If both pressures are equal, the measuring element will not move. If the two pressures are unequal, the element will move proportionally with the pressure difference. Given the two pressures p_1 and p_2, the instrument indicates the difference as

$$\Delta p = p_1 - p_2 \qquad (1\text{-}41)$$

In this example it acts as a differential pressure measuring instrument. If one of the two chambers is hermetically sealed and under vacuum , it becomes an absolute pressure measuring instrument. This is why differential pressure and absolute pressure measuring instruments share the same designs.

The most complicated design criteria of a differential pressure gauges is a link to transmit the pressure forces from one of the two measuring chambers with a low error while hermetically sealed. Various innovations in link technology such as **torsion links** made of metallic or elastomer materials, **bending beams** or **metal bellows** have been developed for this purpose. The link must transmit the displacement of the element, which is generally no more than 0.04 inches. The small displacement is accompanied by a low control force behind the displacement, so the link has to operate with very low friction, and it has to be able to withstand high static pressures.

While these complications can easily be solved using electonics to transmit the deflections, the advantages of mechanical instruments should not be forgotten. Mechanical instruments require no external power supply, which makes them a better choice for safety monitoring applications.

Typical examples and operating principles of absolute and differential pressure measuring instruments are described in the following sections.

Absolute pressure measuring instruments with a diaphragm

As Figure 1.117 shows, a diaphragm (1) separates the pressure chamber (3) from the reference chamber (2). Two bellows (4) seal off the two chambers from the atmosphere. The top housing of the reference chamber above the diaphragm is shaped like the diaphragm for overload protection.

The pressure difference between the evacuated reference chamber (2) and the pressure in the measuring chamber (3) causes a corresponding deflection of the diaphragm. This deflection is transmitted to the movement by a rod (5).

The advantage of this design principle is that the interior of the pressure measuring instrument is vented to the outer atmosphere, allowing various accessories to be installed inside or on the back of the case.

1 Diaphragm
2 Reference pressure chamber
3 Measuring pressure chamber
4 Bellows (corrugated tube)
5 Push rod
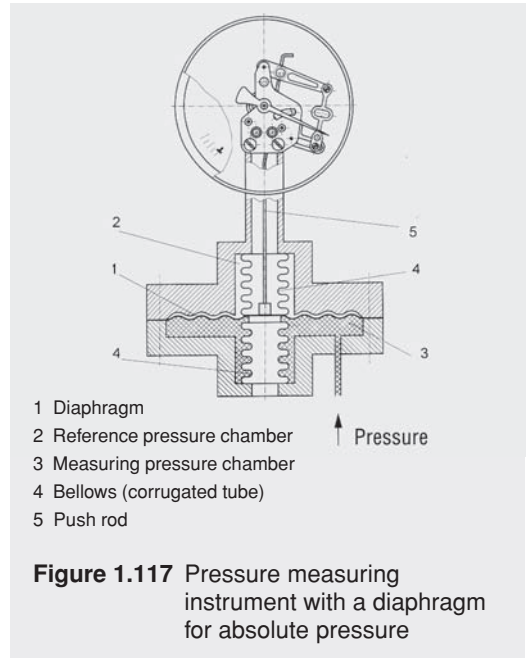
↑ Pressure

Figure 1.117 Pressure measuring instrument with a diaphragm for absolute pressure

Differential pressure measuring instruments with a diaphragm

Connections are rotated 90° in the drawing

⊖   ⊕
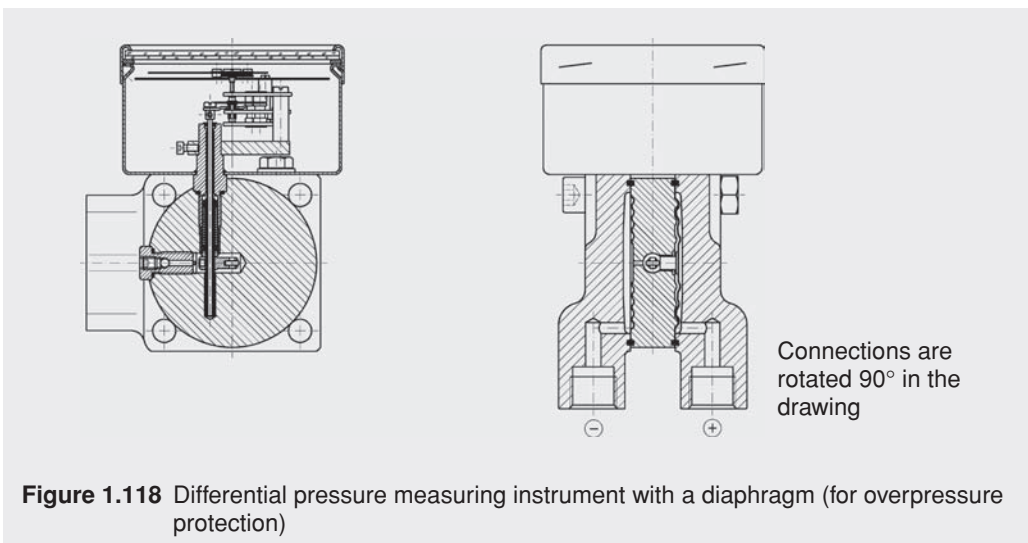
Figure 1.118 Differential pressure measuring instrument with a diaphragm (for overpressure protection)

Design and operating principle

The measuring cell of a differential pressure measuring instrument with a diaphragm (Figure 1.118) consists of two parallel diaphragms, with only a transmission liquid between them. The pressure acts on one diaphragm which is transmitted out of the measuring chamber via a pressure-proof low-friction torsional link. A second diaphragm has a low rigidity and serves as a separating membrane. Behind each of the diaphragms is a diaphragm bed with the same shape as the diaphragm. When the pressures in the measuring chambers differ, there is a deflection of the hydraulically coupled diaphragms proportional to the pressure. If the full scale range is exceeded, the corresponding diaphragm will settle completely in its bed, which means there can be no damage by overpressure. This design eliminates the risks inherent in older designs which used valve systems to prevent overloading. It is also a reliable and safe way to measure very small full scale ranges (16 "H_2O) together with high static pressures (6000 PSI). Both measuring chambers can be vented in order to obtain stable measuring conditions with small pressure differences.

With this design it is possible to add electric accessories such as transmitters and alarm contacts for analog outputs.

Applications:
- monitoring of **filter systems** by indicating pressure loss
- **level measurements** in closed vessels
- f**low measurements** for fluids (liquids, gases and vapors) with indication proportional to the differential pressure

Absolute pressure measuring instrument with a capsule

1	Capsule	5	Pointer
2	Measuring chamber	6	Zero reset screw
3	Transmission lever	7	Range setting screw
4	Movement	8	Ridge support
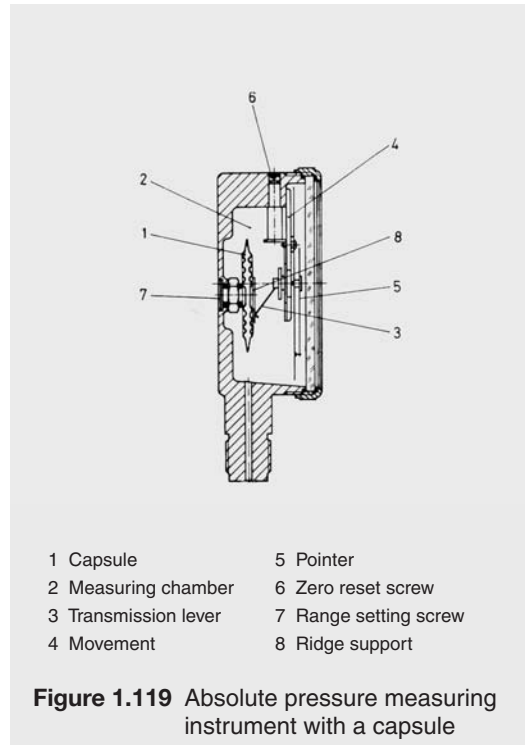
Figure 1.119 Absolute pressure measuring instrument with a capsule

Design and operating principle

The capsule interior (1) is evacuated and serves as the reference chamber. The interior of the case acts as the measuring chamber (2).

A pressure difference between the reference chamber (1) and the measuring chamber (2) causes a deflection of the capsule (measurement displacement). This displacement is transmitted by the transmission lever (3) to the movement (4). The rotation of the pointer (5) indicates the value on the dial. In the event of overpressure, both halves of the capsule come into contact which eliminates the possibility of permanent deformation.

The measuring span (full scale range) is adjusted from the outside using the setting screw (7). Turning the capsule concentrically changes the control point between the ridge support (8) and the transmission lever (3), which in turn changes the operating characteristics of the movement.
The zero point can be adjusted with the zero reset screw (6).

Applications
An absolute pressure measuring instrument with a capsule is suitable for measuring the absolute pressures of gaseous, non-corrosive media containing no oil, grease or suspended particles. Measurements are unaffected by fluctuations of atmospheric pressure. It is used for:
- monitoring of **vacuum pumps**
- supervision of **filling systems** and **vacuum packing machines**, particularly in the food industry
- monitoring of condensation pressures
- determination of the vapor pressure of liquids
- **vacuum distillation.**

Maintenance of the reference vacuum chamber is necessary for reliable operation of absolute pressure measuring instruments. The maximum allowable leakage is best determined by the **pressure rise method**. The **leakage rate** is:

$$q_{leak} = \frac{\Delta p \cdot V}{t} \quad \left[\frac{mbar \cdot l}{s} \right] \qquad (1\text{-}42)$$

where Δp = Pressure rise in mbar
  t = Time in seconds
  V = Volume in liters

Following is an example which shows how precisely the system must be sealed from leakage.

An absolute pressure measuring instrument with a full scale range of 15 PSI and a reference chamber volume of 500 cm^3 should not exceed an

additional error of 1% after five years. To guarantee this requirement, the maximum acceptable leakage rate is:

$$q_{leak} = \frac{0.01 \cdot 1000 \text{ mbar} \cdot 0.5 \text{ l}}{1.6 \cdot 10^8 s}$$

$$q_{leak} = 3.1 \cdot 10^{-8} \frac{mbar \cdot l}{s}$$

Leakage rates of this order of magnitude can only be detected with mass spectrometers using helium as a test gas. Therefore, long-term quality assurance is only possible if the appropriate testing facilities are available for monitoring production.

Gas diffusion in the pressure chamber materials must be eliminated during the operating period, and no structural materials with a low vapor pressure should be used. Welded reference chambers made from stainless steel best meet these demands.

1.4.6.2 Pressure measuring instruments with high overload capability

1 Movement   4 Pull plate
2 Screw   5 Gauge connection
3 Loctite   6 Overload stop
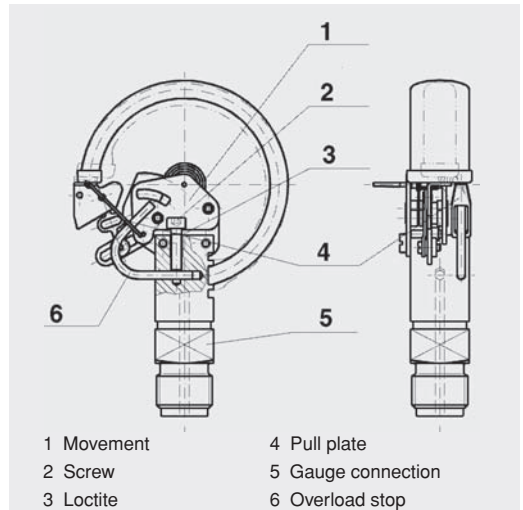
Figure 1.120 Pressure measuring system with Bourdon tube (high ovepressure safety)

Design and operating principle

At low pressures the Bourdon tube moves freely and the pointer travels over the dial proportional to the pressure. At a preset pressure the Bourdon tube "grabs" a spring via the pull plate. As the pressure increases further, the Bourdon tube is restrained by the spring which significantly reduces its displacement, though the small displacement is still proportional to the change in pressure (Figure 1.120).
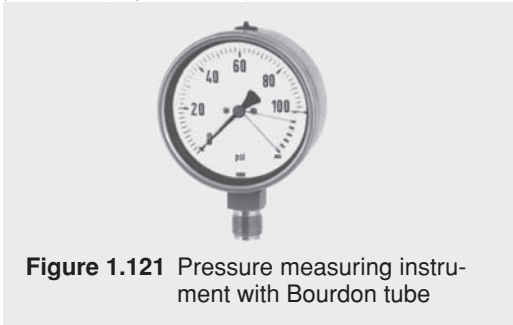
Figure 1.121 Pressure measuring instrument with Bourdon tube

As previously explained in Section 1.4.1.1, the material stress in the Bourdon tube increases slowly, allowing overpressures of up to 5 times the full scale range. Since the spring constant of the overload spring is variable, the overpressure range shown on the dial is also pressure-proportional; only the resolution of the reading is reduced.

1 Diaphragm bed
2 Diaphragm
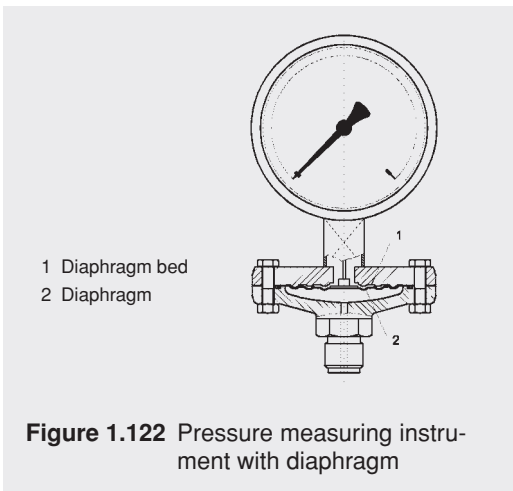
Figure 1.122 Pressure measuring instrument with diaphragm

Figure 1.122 shows the method of overpressure protection used for diaphragm measuring elements, i.e. an identically shaped bed behind the diaphragm. Overload values of up to 100 times the full scale value are possible using this method.

Applications:
- protection against overloading, i.e. during the starting-up of new plants (leak testing of the plant), with the pressure measuring instruments "on-line"
- for increasing the resolution of measuring signals from refrigerating machines during operation and for protecting against the vapor pressure of the refrigerant at room temperature when taking refrigerating machines out of operation.

1.4.6.3 Pressure measuring instruments and pressure transducers for ultra high-purity gases
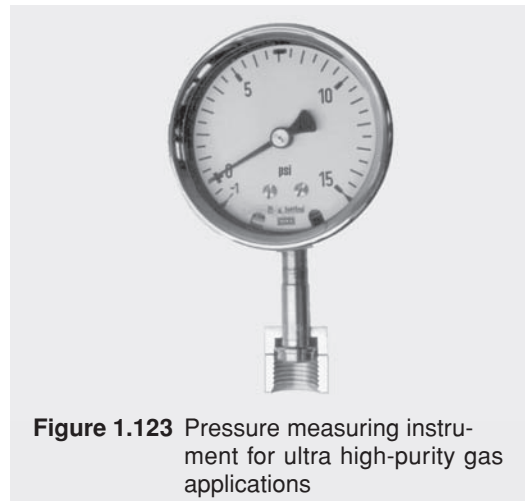
Figure 1.123 Pressure measuring instrument for ultra high-purity gas applications

The following special measures must be taken for pressure measuring instruments used in ultra high-purity gas systems (Figure 1.123):

- top-quality surface finishes of components in contact with the process medium; surface roughness $R_a < 15$ μ in.
- burr-free production of components in contact with the process medium

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- high-quality weld joints produced in an inert atmosphere
- leak testing to extremely tight tolerances with high-purity, filtered and dry helium
- special connections available
- instruments vacuum-sealed in bags.

Special features of the pressure connections:

- one-piece, weld-free sealed socket design
- compatible with all standard high-purity fittings
- solid metal frictionless seal
- fully adjustable pressure gauge orientation
- suitable for ultra-high vacuum as well as high pressure ranges
- leak-free connections guaranteed by polished seal faces
- test bore holes at various points of the sealing area allows any leaks to be detected
- fitting can still be re-used after being removed several times.

| RGV 9/16-18 UNF, Fixed thread | RGV 9/16-18 UNF, With male nut | RGV 9/16-18 UNF With female nut |
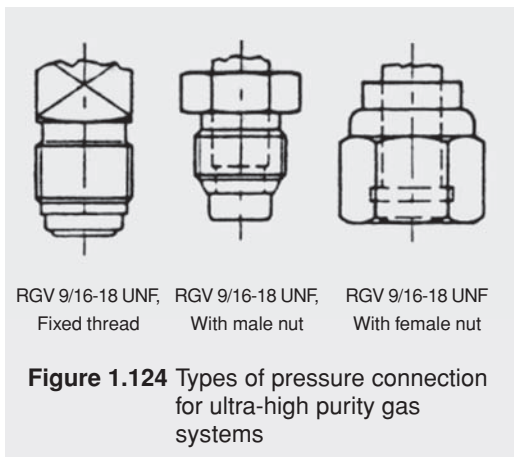
Figure 1.124 Types of pressure connection for ultra-high purity gas systems

Applications:
- **electronics**
  process gas supply for the doping of semiconductor chips
- **gas chromatography**
  exact measurement of head pressure at the separating columns in the high-purity carrier gas current

- **semiconductor technology**
  etching, stripping and metallizing
- **nuclear technology**
  preparation of uranium by the nozzle process, etc.
- **motor vehicle industry**
  calibration gas supply for the measurement of pollutants
- **telecommunications**
  manufacturing of optical fibers (optical cables).

1.4.6.4 Gas density monitors for SF6 systems
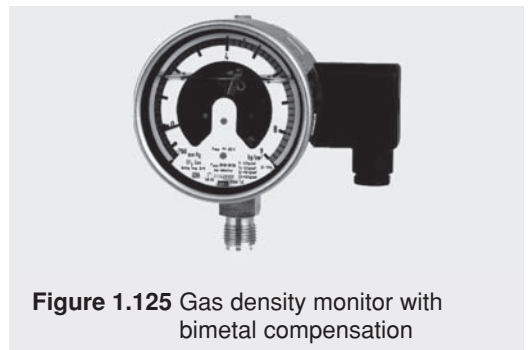
Figure 1.125 Gas density monitor with bimetal compensation

Design and operation

In gas density monitors the measuring element is a Bourdon tube which acts as a pressure/displacement converter. Isochoric pressure changes (isochoric = constant volume; the pressure changes due to temperature fluctuations) should not result in any deflection of the pointer; they are compensated by a bimetal strip acting as a link between the measuring element and the movement (Figure 1.125 and see also Figure 1.91).

The individual displacement values of the measuring element and the particular bimetals are determined using a computer-controlled calibrating machine (a WIKA development) based on the CTS process.

The computer-controlled calculation of this data can also take into account such customer-specific conditions as the filling pressure (at which the monitored gas system is filled), any calibration pressure deviation, and the maximum temperature range requiring compensation.

Figure 1.126 Gas density monitor with remote temperature probe

With the model shown in Figure 1.126, the temperature is measured by an external temperature sensor and converted into a change of length of the link via a bellows.

Temperature-independent pressure changes that cause a response in the measuring element are transmitted to the movement and are shown on the dial by the pointer. The minimum and/or maximum allowable pressures of the monitored gas chamber not caused by temperature changes are used to actuate magnet spring contacts. Non-isolated or isolated magnet spring contacts are available as alarm contacts depending on the customer's specifications. The contacts are permanently set at the factory under falling or rising pressure at customer-specified setpoints.

A standard WIKA measuring system design is used, i.e. connection stem with the Bourdon tube, movement and dial as one unit which is protected by a case. The measuring system is vacuum-proof and has a burst pressure rating of more than 10 times the full scale pressure. Helium leak testing is used to ensure that the leakage rate is less than 10^{-8} mbar l/s.

Depending on the operating conditions (installation in closed rooms or outdoors), the entire measuring system and the electrical alarm contacts are housed in a steel case (weather resistant) or in a stainless steel case filled with a liquid or inert gas (weather-tight).

Gas density monitors are modified pressure gauges used to monitor the density of gases in sealed vessels or systems. Thanks to their special design, the pressure fluctuations caused by changes of temperature in the monitored gas system do not cause any deflection of the instrument pointer. The indicator shows only temperature-independent pressure changes, i.e. changes of density, caused i.e. by leaks. These instruments must be installed so that the temperature of the density monitor is exactly the same as the temperature of the gas. The pointer movements can be used to trigger alarm contacts.

Applications:
- gas-filled **high-voltage switches** and **high-power transformers**
- underground gas-filled **power and telecommunication cables**
- **gas pressure accumulators** and gas-filled **fire extinguishing systems.**

For the applications above, the insulating properties of the gas filling are determined by the density of the gas. Thus the use of gas density monitors to indicate only temperature-independent changes of pressure and to send a signal output when a specific pressure limit is reached.

1.4.7 Special designs and optional accessories

Pressure measuring instruments may be supplemented by accessories or adapted to special measuring conditions according to their specific application. Some of the most popular special designs and options which have not been detailed elsewhere in this handbook are described below.

1.4.7.1 Pressure measuring instruments for oxygen and acetylene

Pressure measuring instruments for oxygen are manufactured without oil and grease. They must also be kept free of oil and grease during storage and use, since even small traces may result in explosions.

Acetylene forms explosive compounds with copper (i.e. copper acetylide). Therefore those components which come into contact with acetylene (connection and measuring element) should be made of copper alloys with a maximum copper content of 70%.

Safety specifications for instruments used with these potentially hazardous process media are outlined by Underwriter's Laboratories specification UL-252A (low pressure) and UL-404 (high pressure). General specifications are also addressed in the documents ASME B40.1 (U.S.) and ISO 5171 (Europe).

1.4.7.2 Calibration with other pressure media

For instruments with a low pressure range, 30 PSI and lower, the gauge readings can be affected by the weight of the process medium inside the Bourdon tube element. If the instrument is calibrated with a medium that is different than the process medium, small reading errors are possible. However, as a rule the error is small and within the specified accuracy of the instrument.

For test and precision test gauges, it is important to know the type and make-up of the process media (liquid or gas) prior to manufacture so that the proper calibration can be made to the instrument.

Pressure measurement standards suggest that gauges with ranges 30 PSI and lower be calibrated with a gas. If a process medium other than gas is used, this should be marked on the dial.

1.4.7.3 Bourdon tube with tip bleed

To assure precise measurements it is sometimes necessary to fill the Bourdon tube completely with the liquid process medium (instead of allowing an air bubble to be trapped at the end of the tube when pressure is applied). To accomplish this, a tip bleeding hole is added to the end of the Bourdon tube. When the instrument is put into service, the air is first drawn out and the bleed tip is closed. An alternative form of venting the media is referred to as capillary bleeding. A flexible capillary tube comes out of the end piece and attaches to the inside of the case where it is closed with a valve screw. To ventilate the system, the screw is opened until process medium begins to escape. Appropriate safety precautions must be taken when working with hazardous substances.

1.4.7.4 Bourdon tube with filling

For applications where the process medium is not allowed to enter the Bourdon tube (for instance when substances solidify when cooled and would clog the measuring element), it is possible to fill the Bourdon tube and connection with mineral oil, silicone oil or glycerine. This filling needs to be topped off from time to time, however, so capillary bleeds are recommended in these cases. The Bourdon tube, connection and capillary are then filled, i.e. with silicone grease. Then, the system can be topped off from the outside via the capillary bleed.

1.4.7.5 Extension of the lower scale range (retard gauges)

The purpose of extending the scale range is to improve readings in the lower range of the scale. This is advantageous, for example, on low-pressure pressure gauges for steam heating systems. Extending the scale is accomplished by using a Bourdon tube that corresponds to a lower scale range. At a displacement that is roughly equivalent to a pointer deflection of 135°, the measuring element comes to rest against a support bracket which has the same radius of curvature as the Bourdon tube. Then, the only portion of the Bourdon tube that can move is between the end of the support bracket and the end piece (Figure 1.127). This suppresses, or "retards", the movement of the Bourdon tube and slows the travel of the pointer.

The size of the expanded lower scale area is limited, particularly on Bourdon tube gauges where there is a risk of the tube being overpressured. Expanded lower scales are possible on Bourdon tube gauges with full scale ranges of up to 400 PSI. Depending on the material used for the

measuring element the expanded area can be as much as 25% of the full scale range, distributed over half of the scale.

With diaphragms it is possible to have even larger expanded lower scales. It should be noted, however, that pressure gauges with expanded lower scales cannot be calibrated to the same accuracy throughout the entire scale. The retarded area with always have a significantly reduced accuracy compared to the expanded scale area.

1.4.7.6 Dual scales

Pressure gauges are often used with a dual scale dial for easy unit conversion in the field (for example PSI and BAR scales). Dual scale dials are also used to show the relation between pressure and a different unit of measurement such as temperature, weight, or quantity.

1.4.7.7 Scales for direct measurement of force

Pressure gauges are used on hydraulic dynamometers, tensile testing machines and hydraulic presses not only to measure pressure (force/unit area) but also force. To eliminate the need to convert the pressure reading to a force, the force scale is printed directly onto the dial either in addition to or in place of the pressure scale.

In these cases, the customer must specify the conversion between force and pressure to the manufacturer.
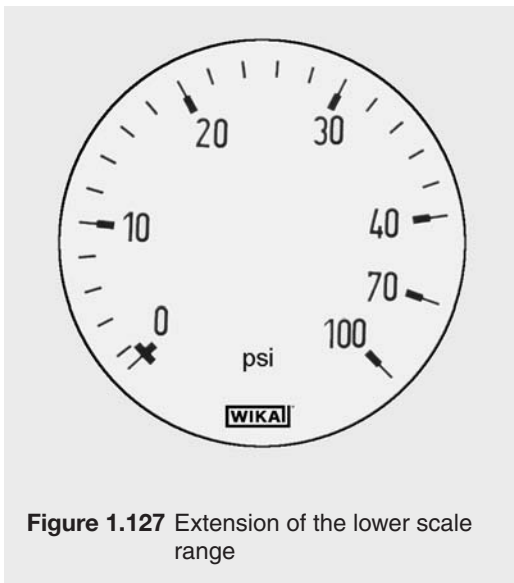
Figure 1.127 Extension of the lower scale range
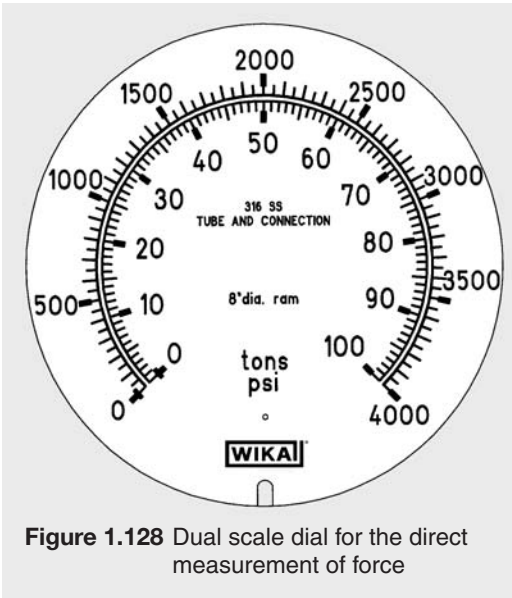
Figure 1.128 Dual scale dial for the direct measurement of force

Example (Figure 1.128)
A pressure gauge with a range of 0 to 4000 psi and a working piston diameter of 8 inches, the calculation would be:

$$F \text{ [tons]} = \frac{p \text{ [psi]} \cdot A \text{ [in}^2]}{2000} \qquad (1\text{-}43)$$

$$= \frac{4000 \cdot (4")^2 \cdot \pi}{2000}$$

$$F \text{ [tons]} = 100 \text{ tons}$$

Pressure gauges with a force measuring scale can only be used for calibration purposes when they also show the equivalent pressure scale, such as PSI or BAR, on the dial in conjunction with the force scale.

1.4.7.8 Temperature scale

Since a direct relationship exists between the pressure of saturated vapors and their temperature, pressure gauge dials can be supplemented by one, two or three temperature scales, each of which applies to a different process medium. These dials are typically used for heating and refrigeration applications.
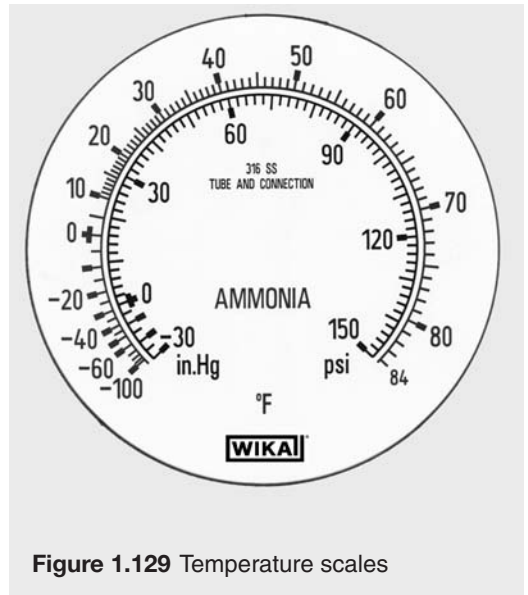
Figure 1.129 Temperature scales

The temperature scales are based on the common vapor tables of refrigerants (saturated), with a reference pressure of 29.89"Hg (1013.25 mbar).

The figures are also based on chemically pure liquids. Considering that the process medium rarely exists in pure form and that the reference pressure often deviates from 29.89"Hg, the corresponding temperature readings can only be assumed to be approximate, but still sufficiently accurate for most purposes.

1.4.7.9 Scales with compensation for difference in levels

In some applications, the pressure gauge has to be positioned either higher or lower than the pressure tapping point (Figure 1.130). With liquids and condensates, the reading is then affected by the hydrostatic pressure of the liquid. If the pressure gauge is installed underneath the pressure tapping point, the reading at zero pressure will be above the zero point on the dial. If it is installed above the pressure tapping point, the reading at zero pressure will be lower than the zero point on the dial.
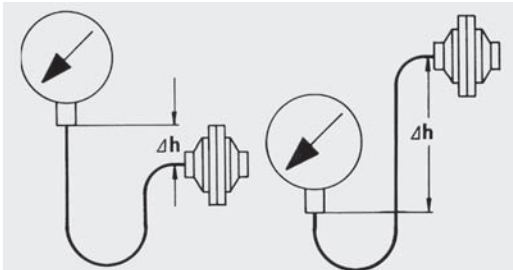
Figure 1.130 Compensating for the difference in levels when working with liquid process media

The change Δp is derived from the change of density of the liquid to air $(\rho_F - \rho_L)$ and the difference in levels Δh:

$$\Delta p = (\rho_F - \rho_L) \cdot g \cdot \Delta h \cdot 10^{-5} \text{ (psi)} \quad \textit{(1-44)}$$

where Δp = Displacement of the measuring range (psi)
ρ_F = Density of the filling liquid (lb/ft^3)
ρ_L = Density of air (0.0751 lb/ft^3)
g = Acceleration due to gravity (32.2 ft/s)
Δh = Difference in levels (ft)

For liquid media applications where the gauges will be mounted above or below the tapping point, the difference in height should be specified to the factory. With this information, the gauge can be properly calibrated for this special application by compensating the reading at the zero point. The reference point of the gauge is the tip of the connection.

Not all sizes and ranges of gauges can be calibrated to eliminate the hyrdostatic pressure errors as outlined above.

The following table provides a guideline:

Pressure gauges with a C-shaped tube

Size	Bourdon tube material	Full scale deflection [PSI]	Suppression [maximum]
1^1/$_2$" to 2^1/$_2$"	Copper alloy	up to 400	20%
		> 400	15%
3" to 10"	Copper alloy	up to 400	30%
		> 400	15%
	316 SS	up to 400	20%
		> 400	15%

Pressure gauges with helical tubes

Bourdon tube material	Full scale deflection [PSI]	Suppression [maximum]
Copper alloy	up to 6000	20%
316SS	up to 10,000	15%

Pressure gauges with a diaphragm

It is possible to have a maximum static head pressure of approximately 30% for all scale ranges using standard measuring element materials.

Example

A maximum static head pressure of 30 PSI (= 30%) can be compensated for when using a 4" size Bourdon tube pressure with a full scale value of 100 PSI. The remaining range therefore extends from 30 to 100 PSI over the 270 degree scale of the dial.

Basically there are two options available for labeling the scale. Which of the two is chosen depends mainly on the application:

1. Increments are printed on the dial that directly correspond to measured values (in the current example 30 to 100 PSI)

2. The static head pressure is calibrated into the normal scale starting at "0". In the example above this would mean:

   Scale value 0 PSI equals a real pressure of 30 PSI,
   Scale value 10 PSI equals a real pressure of 40 PSI,
   Scale value 20 PSI equals a real pressure of 50 PSI,
   Scale value 30 PSI equals a real pressure of 60 PSI, etc. up to
   Scale value 70 PSI equals a real pressure of 10 PSI.

This is referred to as a "compensation" of 30 PSI.

Option 1 is always chosen when the actual pressure needs to be read.

Option 2 is an advantage when measuring relative pressures.

1.4.7.10 Luminous dials

When pressure gauges are used in dark areas, it is possible to use **luminous paint** for the pointer, scale, labeling or dial background. In special cases it is even possible to install a small electric light.

1.4.7.11 Mark pointers

In some applications the pressure is not allowed to exceed a maximum limit. In addition to other safety precautions the pressure gauge should also give the observer a visual warning that the maximum pressure has been reached. The easiest way to do this is with a red mark pointer that is also longer than the printed increment lines on the dial. If a specific scale value must be marked when the instrument is put into operation, the instrument comes with a red mark pointer that can be adjusted from the outside or after removing the cover ring. These pointers give no indication, however, whether the pressure has passed the maximum or minimum value at some other time.

1.4.7.12 Drag pointers

The drag pointer allows you to check the maximum or minimum pressures to which the instrument has been exposed. A "maximum" drag pointer indicates the maximum pressure the gauge has experienced and alternatively a "minimum" drag pointer show the minimum pressure.

The drag pointer is mounted freely on the window. When pressure is applied, the instrument pointer moves the maximum drag pointer for as long as the pressure rises. When the pressure falls, the maximum drag pointer remains at this maximum value while the instrument pointer continues to indicate elsewhere on the dial. The minimum drag pointer works in the same way. A reset knob on the window allows the drag pointer to be reset at any time.

1.4.7.13 Suppressed zero

Readings in the lower portion of the dial range are sometimes not as important as those in the upper portion of the dial range. For example, with water levels in elevated containers, the pressure in the water between the bottom of the tank and the pressure gauge is constant and therefore of no interest. In this case, the Bourdon tube can be pre-stressed to suppress that initial, constant pressure. Therefore the gauge would only indicate pressure increases above that constant pressure. This can also be accomplished by using a special link assembly in the movement. Regardless of the method, the scale suppression should not exceed 30% of the full scale value of the gauge. (see Section 1.4.7.9).

1.4.7.14 Extended pointer shaft

If pressure gauges with certain accessories, for example electric remote transmitters, it is necessary to install a measuring system with a pointer shaft that extends through the rear of the case. The drive shaft of the remote transmitter is mounted to the pointer shaft where it exits the rear of the case.

1.4.7.15 Safety glass

To prevent injury in the event of window breakage, pressure gauges can be supplied with shatterproof laminated safety glass. Plastic windows, such as polycarbonate, are also an option.

1.4.7.16 Special protection during shipment

Some pressure gauges with sensitive measuring elements and movements have little inherent protection from external shock and need special protection during shipment. One way this can be accomplished is by securing the measuring element in place with a shipping screw. This screw must be removed prior to putting the instrument into operation.

1.4.8 Measurement data and standards concerning applications

1.4.8.1 Full scale range and maximum operating range

The full scale range of a pressure gauge is understood to be the entire length of the graduated dial. The maximum operating range is that part of the full scale range which may be continuously used for operation at static pressure. The lower limit of this range is generally taken to be the first tenth of the full scale range (this allows for the steady increase in absolute measuring error). The upper limit depends on the load capacity of the measuring element in terms of its yield limit. The **upper limit of the maximum operating range** is equivalent to the full scale pressure printed on the dial. For standard pressure gauges, the upper limit of the maximum operating range corresponds to 75% of the full scale. For industrial-grade pressure gauges, the upper limit of the permissible range equals 100% of the full scale value. In applications with fluctuating loads only part of the maximum operating range can be used, as was explained in the description of the Bourdon pressure measuring element (see Section 1.4.1.1). Recommendations for maximum loading and safety concerns are outlined in ASME B40.1.

Pressure spikes during operation are not allowed to exceed the maximum operating range of the pressure gauge. If this cannot be avoided, **overpressure protection** devices must be installed upstream of the instrument. Such devices close the line immediately in the event of a sudden pressure rise and slowly when the pressure rises gradually (the closing pressure is a function of the time-related pressure curve).

Sudden pressure changes exceeding 10% of the full scale value per second can make reading of the measured value difficult and reduce the life of the gauge. In this case, the gauges should be damped, for instance with a liquid (see Section 1.4.4.3).

1.4.8.2 Accuracy of the indication

The required **accuracy level** is an important criteria for instrument selection, since the values of a unit of measure (in our case pressure) determined with a measuring instrument will never be error-free.

The **error** E_{indic} is the difference between the value X_a indicated or output by the instrument and the value X_r considered to be the correct value as determined by a measurement standard.

$$E_{Indic} = X_a - X_r \qquad (1\text{-}45)$$

The **relative error** E_{rel} is the error E_{indic} of a measuring point relative to its correct value.

In pressure measurement systems the error is considered relative to the end of the measuring range, which in the case of indicating instruments is the full scale value (fsv). The relative error is then

$$E_{rel} = \frac{X_a - X_r}{fsv} \qquad (1\text{-}46)$$

If there is any doubt, the reference value should be indicated when quoting the error in order to avoid misunderstandings.

Multiplication of the relative error by 100 gives the magnitude as a percent value. If several errors are equally determined over the measuring range, an error profile of the instrument can be drawn up (see Figure 1.131).
The error is determined with increasing values of the reading and - after a specified waiting period - with decreasing values.
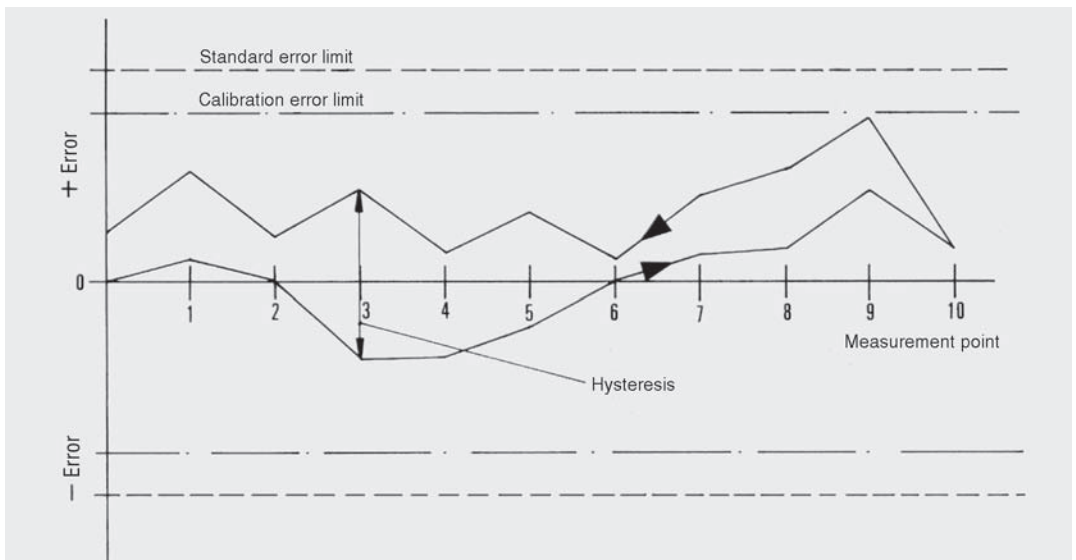
Figure 1.131 Types of error on pressure gauges

For pressure gauges with flexible measuring elements, the individual errors on the error curve within a specific accuracy grade defined by ASME B40.1 are not allowed to exceed the maximum error for the accuracy grade.

This error band has two limits: the **calibration error limit** and the **standard error limit** (see Figure 1.131).

The calibration error limit indicates the maximum operating error of the new instrument, whereas the standard error limit applies after the instrument has been subjected to a specific number of dynamic and continuous loads (operating conditions).

The **accuracy grades** and the **error limits** are listed in the following table.

Accuracy Grade	Lower 1/4 of scale	Middle 1/2 of scale	Lower 1/4 of scale
	% of span		
4A	± 0.1	± 0.1	± 0.1
3A	± 0.25	± 0.25	±0.25
2A	± 0.50	± 0.50	±0.50
1A	± 1.0	± 1.0	±1.0
A	± 2.0	± 1.0	± 2.0
B	± 3.0	± 2.0	± 3.0
C	± 4.0	±3.0	± 4.0
D	±5.0	±5.0	±5.0

The **hysteresis** is determined from the magnitude of the reading in the falling direction minus the magnitude of the reading in the rising direction. The reading is not allowed to exceed the limit values listed in the above table.

The limit values are positive and related to the magnitude of the start and end scale value under vacuum or positive pressure, i.e. they are related to the measuring span (full scale range) under vacuum and positive pressure.

As standard equipment this test requires a pressure gauge with an error smaller than 25% of the calibration error limit of the instrument to be tested. The reading takes place after 3 slight taps on the pressure gauge case. The **minimum number of measuring points** equally distributed over the range should be:

ASME B40.1 Accuracy	Minimum # of measuring points
ASME Grades 2A, 3A, or 4A	10
ASME Grades B, A, or 1A	5
ASME Grades C & D	4

The beginning and end of the range are considered as measuring points.

The following list shows the uses of gauges with each accuracy grade by application type.

ASME Grades 2A, 3A & 4A: for precise measurements in the laboratories and workshops
ASME Grades A & 1A: for industrial pressure measurement on machinery and production lines.
ASME Grades B, C & D: for simple monitoring applications without precise requirements.

1.4.8.3 Process fluids

The physcial and chemical properties of liquid or gaseous process media can vary widely. It is obvious that the various materials used in pressure gauges will react differently with the various process fluids. Certain metals are destroyed by aggressive gases and need to be protected against the process fluid. This is often accomplished by applying a protective coating or by using a chemical seal. In certain cases, the reaction of the process fluid with other substances (oxygen with oil, acetylene with copper and copper alloys containing more than 70% copper) may lead to an explosion.

The materials used for parts in contact with the process fluid, referred to as the **wetted parts**,

must be properly selected. Typically the manufacturer and the end-user work together to determine the most appropriate materials to use for the wetted parts.

For liquid process fluids, the viscosity must be considered because of the relatively narrow pressure port. Viscous liquids pose problems for Bourdon tube pressure gauges since viscous process fluids may have difficulty getting into the Bourdon tube, if at all. Diaphragm systems, especially with a process flange (see Figure 1.71), are a better solution.

Details of the effect of process fluids on materials can be found in the chemical resistance tables (see Section 4.2).

If the temperature at the measuring point is greater than the maximum operating temperature of the pressure gauge, a long measuring line, siphon or chemical seal with a capillary line must be connected upstream of the measuring instrument. The error due to the difference of temperature between calibration and operation must be considered.

When gases and liquids are under high pressure, the energy stored in the measuring element presents a considerable risk to operating personnel. Any person in front of the measuring instrument at the moment any pressurized parts rupture could be injured by the splintering window or by escaping process fluid.
Pressure gauges with a safety design (solid front) should used to eliminate such risks. They are highly recommended for liquid-filled pressure gauges.

The regulations governing accident prevention must be observed when taking pressure measurements with dangerous substances such as acetylene, oxygen, combustible or toxic substances. A selection of major regulations, specifications and directives concerning safety can be found in the appendix.

1.4.8.4 Environmental conditions

If the transmission of shock to the measuring instrument cannot be prevented, instruments with a damped movement or liquid filling should be used.

The accuracy grade (sometimes indicated on the dial) applies to an ambient temperature of 68°F ± 3.5°F (20 °C ± 2 °C). Other temperatures cause additional errors, the size of which depends on the type of instrument.

In liquid-filled instruments the viscosity of the filling liquid increases at lower ambient temperatures. This causes increased damping and a slower pointer response time.

Pressure gauges installed outdoors should be sufficiently protected against water to avoid freezing at temperatures below 32°F (0 °C).

Special coatings or cases made of resistant materials resist attack from corrosive ambient air.

Analog and digital pressure transmitters and transducers.

WIKA®

1.5 Pressure transducers, pressure measuring converters and pressure transmitters with analog and digital circuits

The most common types of electrical pressure measuring instruments used today were detailed in Section 1.3.2.2. Section 1.5 will now give more detailed information on how the pressure measurements are processed and address typical problems found in common applications such as the influences of temperature and other variables.

1.5.1 Definition of a pressure transducer

Pressure transducers are an advanced form of pressure sensor element. The simplest form of an electrical pressure measurement system is the pressure sensor. It is the pressure sensor which changes the physical variable "pressure" into a quantity that can be processed electrically. A pressure transducer is the next level of sophistication. In a pressure transducer the sensor element and housing are in electrical contact and have a pressure connection.
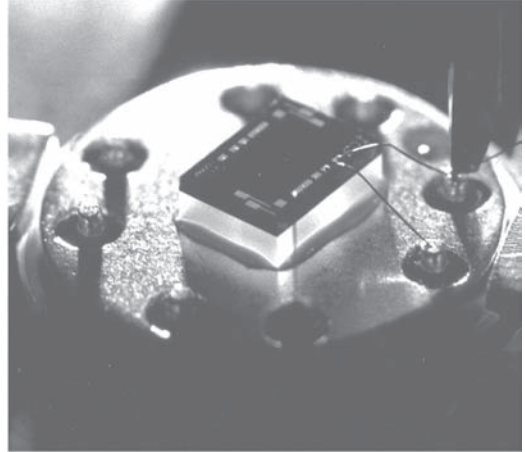
Figure 1.132b A chip with bond wires on a TO-8 carrier

Typical output signals from pressure transducers are between 10 mV and around 100 mV, depending on the sensor type. These signals are not standardized, however, nor are they compensated. With thin-film type pressure transducers it is customary for just the sensor element to be welded to the pressure connection and then bonded electrically. Piezoresistive pressure transducers, on the other hand, require far more production steps since the semiconductor sensor element has to be protected from the effects of various media by a chemical seal. The production of piezoresistive pressure transducers consists of the following steps.

1. The elementary sensor is joined to the carrier. TO-8 casings with 8 contact pins and an insulated glass bushing are often used as carriers. The chips are either glued or soldered to the carrier, depending on the manufacturer.

2. Then the TO-8 chip is joined to a pressure-bearing case by welding, clamping or soldering.
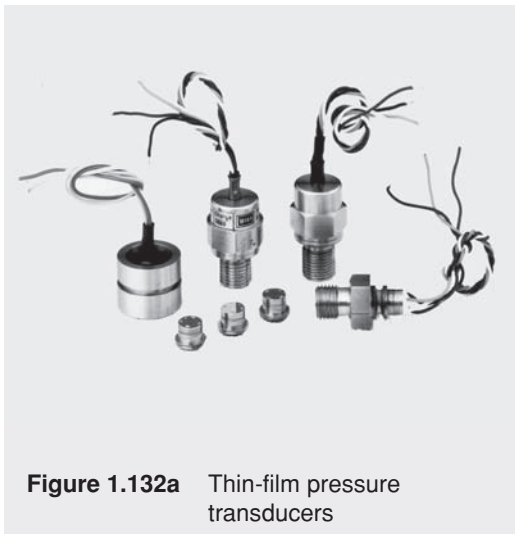
Figure 1.132a Thin-film pressure transducers
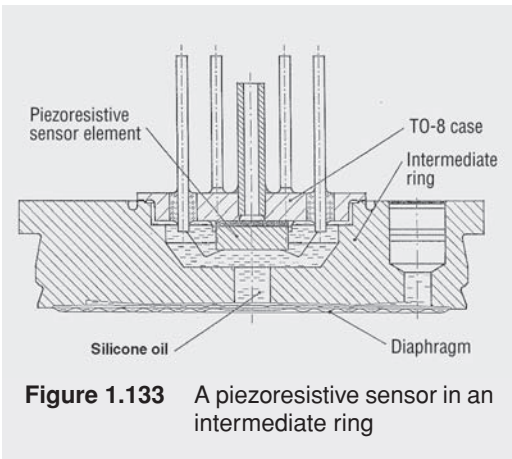
Figure 1.133   A piezoresistive sensor in an
intermediate ring

3. The case is then welded to a front diaphragm.
This diaphragm is normally designed with corru-
gations and is approximately 0.1 mm thick. Today
some pressure transducers are equipped with
plastic diaphragms (Figure 1.134). Although eco-
nomical, this material is not compatible with all
process media. In most cases the diaphragm is
made of stainless steel.
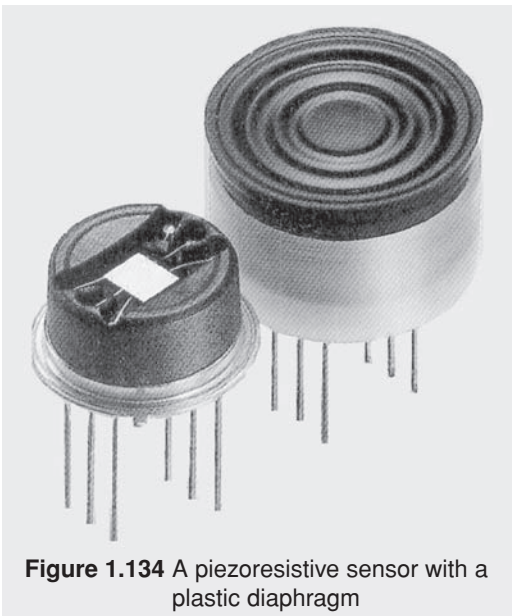
Figure 1.134 A piezoresistive sensor with a
plastic diaphragm

4. Next the pressure transducer is filled with a
pressure-transmitting liquid (silicone oil). To do
this, the pressure transducer is placed in a closed
container which is then evacuated. Once the nec-
essary vacuum is reached, the silicone oil is
drawn into and completely fills the system without
any trapped pockets of air.
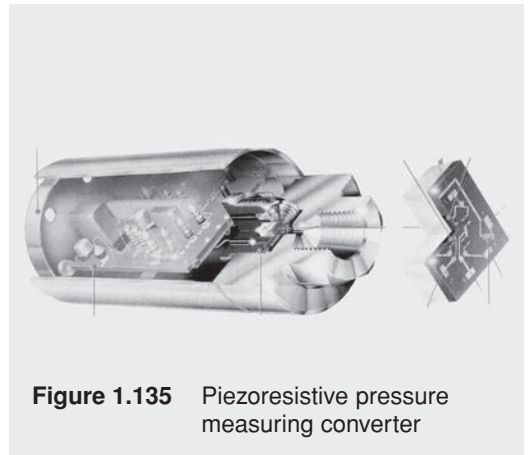
Figure 1.135   Piezoresistive pressure
measuring converter

5. Finally the pressure transducer is sealed.
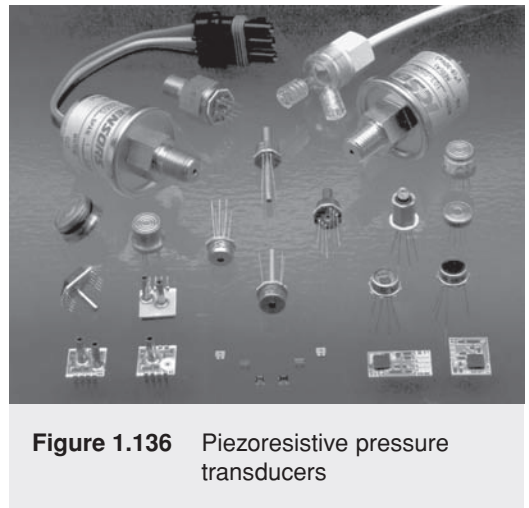
Figure 1.136   Piezoresistive pressure
transducers

1.5.1.1 Pressure transducers and their specifications

Output signal
Pressure transducers do not contain any active electronics and therefore no components which stabilize the supply voltage. This means that the output signal is always proportional to the supply voltage. Typical output signals are, for example, 2 mV/V with thin-film pressure transducers and 100 mV/V with piezoresistive pressure transducers. The output signal is proportional to the supply voltage.

Temperature error
Every pressure transducer not only has a sensor-specific output signal but also a temperature error that is typical for the particular sensor type. The following diagram shows the typical characteristic curves for the temperature errors of:

a) thin-film pressure transducers
b) piezoresistive pressure transducers
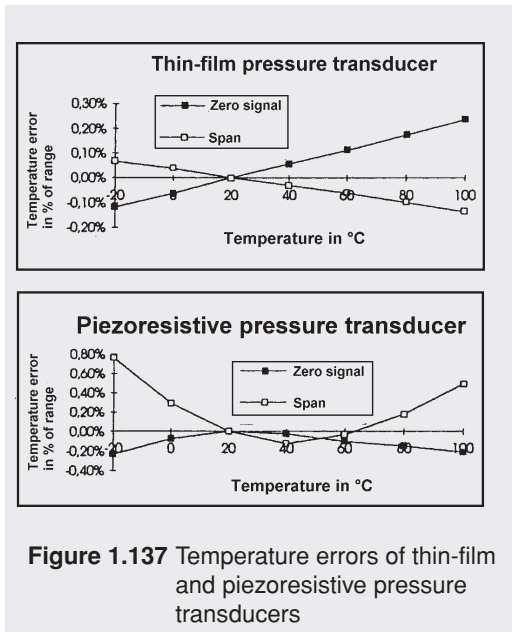
Figure 1.137 Temperature errors of thin-film and piezoresistive pressure transducers

As this diagram shows, thin-film pressure transducers have a characteristic curve that it is far easier to compensate than that of pressure sensors made of semiconductor materials.

Linearity
The linearity figures specify the value of the maximum deviation of the characteristic curve from the maximum line through zero and the end point.

1.5.1.2 Pressure measuring converters

Pressure measuring converters represent the next level of assembly of pressure measuring instruments. They have standardized output signals that can be relayed directly to follow-up control units, for example 4 to 20 mA output.
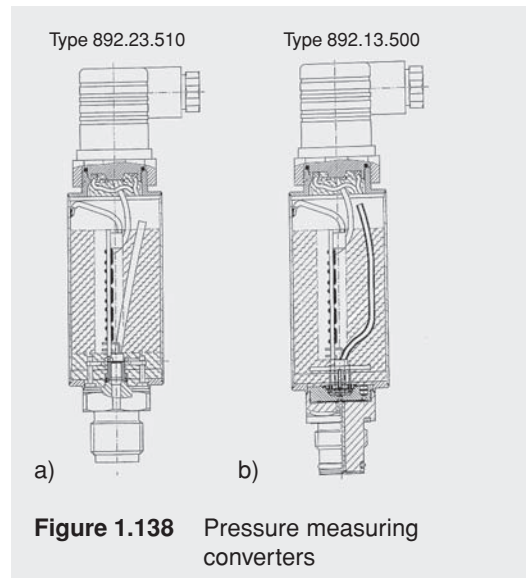
Figure 1.138 Pressure measuring converters

They consist of:
- a basic sensor (b) Piezo, (a) Thin-film strain gauge
- pressure connection
- signal processing electronics
- case
- electrical connection

Due to the large number of different applications, there has been no standardization on any one design type. However certain trends have been noted, such as

Pressure connection	$^1/_2$" NPT, 316SS
Output signal	4 to 20 mA, 2-wire
Case material	316SS

The specifications and definitions of characteristic data for electric pressure measuring systems are not documented by any officially recognized organization in the U.S. Therefore it is difficult to compare products from one manufacturer to another.

1.5.1.3 Technical data and their definition

It is customary to state the following information in technical descriptions of pressure sensors, pressure transducers and pressure measuring converters.

Measuring range / measuring span

The measuring range is the span between the start and the end of the measurements. The error limits stated in the data sheet apply within this measuring range. The type of pressure, for instance positive pressure, vacuum pressure, absolute pressure or differential pressure, is also specified in order to define the measuring range.

Maximum pressure range

The maximum pressure defines the pressures at which a pressure measuring converter can be exposed without it suffering permanent damage, i.e. zero-point offset. The pressure measuring converter is allowed to deviate from its specified technical data in the area between the full scale range and overload pressure limit. The maximum pressure limit is usually determined by the sensor type.

With piezoresistive pressure measuring converters the maximum pressure is identical to the burst pressure. In thin-film pressure measuring converters, on the other hand, there are significant differences between maximum pressure and burst pressure. This is due to the silicone and stainless steel sensor. While steels enter a flow phase when they exceed their flexible range, brittle materials have a linear characteristic up to the bursting point.
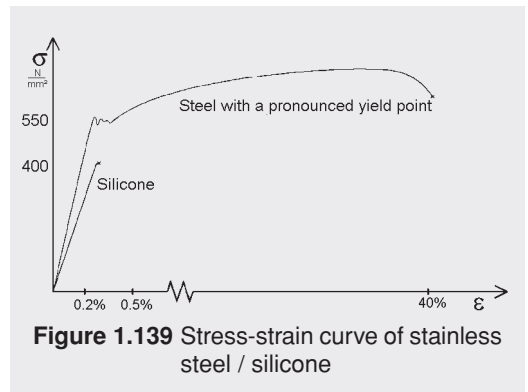
Figure 1.139 Stress-strain curve of stainless steel / silicone

Burst pressure

Burst pressure defines the pressure range which, if exceeded, can lead to the total destruction of the pressure measuring converter and therefore to a loss of the process medium.

Power supply

An power supply is required to operate pressure transducers and pressure measuring converters. The most common is 24 V direct current. Because of their voltage-stabilizing components, pressure measuring converters usually have a bigger supply voltage range of i.e. 10 to 30 VDC. Between this range there should be no effects due to variations in the supply voltage.

For example, if the pressure measuring converter is calibrated at the factory with a power supply of

24 VDC, there should be no change of accuracy if the converter is actually operated with just 12 VDC. The effects of supply voltage variation should not generally exceed 0.1% per 10 V.

Output signal (analog, digital)

Current and voltage signals have become established as the most popular for output signals. Exactly which output signal is chosen depends mainly on the indicating and control devices to which the pressure measuring converters send their output signal. As a general rule it can be said that current signals are less susceptible to interference during transmission than voltage signals.

Systems with 4 to 20 mA in 2-wire technology are becoming increasingly popular in industrial plants. The main advantage of this technology is that the power supply and measuring signal are both carried over the same connection lines, which for large installations offers a notable saving in wiring costs.

At the same time the higher zero point (4 mA) allows the measuring point to be monitored for open circuits and device failure, because in these cases the flow of current would drop below 4 mA. This change can be used in the monitoring units, i.e. to trigger an alarm.

From the automotive industry there is also an increasing demand for so-called ratiometric voltage signals. This means, for example, that the supply voltage range is defined as 5 V +/- 10% and the output signal specified as 0.5 to 4.5 VDC +/- 10%. If the supply voltage amounts, for example, to 4.5 V (-10% of the full scale range), the output signal will equal 4.0 V (4.5 V less 10%). This output signal saves several electronic components and allows cheaper pressure measuring converters.

With current outputs the maximum load is specified in addition to the output value. This load is called the maximum allowable load impedance.

$$R_A \text{ [Ohm]} = (U_B \text{ [V]} - U_B \min)/0.02 \text{ [A]} \quad (1\text{-}49)$$

R_A = Load impedance in ohms
U_B = Actual supply voltage in volts
$U_B\min$ = Minimum allowable supply voltage specified in the data sheet

In practical applications the actual load used should be much smaller than the maximum allowable load in order to eliminate measuring errors due to extremely high contact resistances.

There is also a certain demand for frequency outputs in special applications, for example mining.

Another type of signal now gaining importance is the digital output signal, which with the right software can then be input directly into microprocessor-based systems.

Response time

The response time defines the period of time needed by the output signal when there is a sudden change of pressure. It is usually quoted within a range of 10% to 90% of the measuring range.

With modern sensor types the response time is very short because of the small displacement of the diaphragms. When specifying the response time, the user must consider whether he requires a continuous signal or, for example, whether he has to be able to measure at high speed in order to detect any pressure peaks. Normally the necessary damping of the signal is performed by the amplifier electronics.

Accuracy and conformity error

The accuracy is stated as a percent of the full scale deflection and usually specifies the maximum deviation of the measured characteristic curve from the ideal line between the start and end of the measurement. This method is commonly referred to as **terminal based calibration** and is prevalent in Europe because European standards state that only the maximum single error from linearity, reproducibility and hysteresis is used to determine the conformity error. With modern sensor systems, hysteresis and reproducibility are negligible.

Figure 1.141 B.F.S.L. calibration

Figure 1.140 Terminal-based calibration

In the U.S., the standard method for determining accuracy is BFSL (best fit straight line). The B.F.S.L. method calculates the initial lines, which are then applied to the actual measured values to keep the deviations as small as possible. As a rule of thumb there is a factor of 2 difference in accuracy between terminal based calibration and B.F.S.L. calibration (1% with the terminal-based calibration equals approximately 0.5% with B.F.S.L. calibration).

Hysteresis

Hysteresis is the difference in the output signals at a given pressure between when the applied pressure is rising and falling.
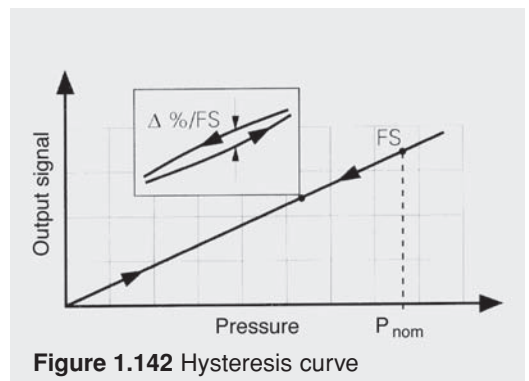
Figure 1.142 Hysteresis curve

With diaphragm deflections in the µm-range, today's sensor technologies usually have hysteresis values significantly less than 0.1%.

Temperature ranges

Process fluid (media) temperature

The process fluid temperature defines the range of temperature which the process fluid is allowed to reach without causing the pressure transducer to fall out of the standard specifications. Pressure measuring transducers with an built-in cooling element are used if the process fluid temperatures are high, i.e. up to 300°F (150 °C) (Figure 1.143). Chemical seals need to be used for process fluid temperatures of up to 750°F (400 °C) (see Section 1.6).

Ambient temperature

The ambient temperature defines the range to which the pressure transducer can be exposed without causing the pressure transducer to fall outside of standard specifications or suffer any damage to the case or electrical connection.

Compensated temperature range

The most important temperature limit consideration is the compensated temperature range. The temperature error limit specifications apply to the compensated temperature range only. Errors outside of this range are higher.

The temperature error must be added to the errors that occur due to linearity, hysteresis, and repeatability. The total error depends mainly on the sensor systems used and is conditional on the type of internal compensation.

Specific compensation data for each particular pressure transducer can be determined by an analog-digital circuit arrangement and saved in the integrated memory. These types of compensated pressure transducers have no additional temperature errors within a specially defined temperature range.

Types of electrical connections

Among electrical connections there is a continuing trend toward using 4-pole right-angle plugs (per European DIN 43650 specifications). Today the most popular choice for low-price pressure transducers are 6-4A 1 MMT appliance plugs. Installation and replacement is easier with both of these plug systems than with, for example, flying leads.

Flying leads are needed if the plug connectors are not able to meet the application's protection requirements, which is almost always the case with well probes or level probes. In these applications the need for water-tightness at submerged depths of up to 850 ft. (250 m) can only be met by using specially designed flying leads.
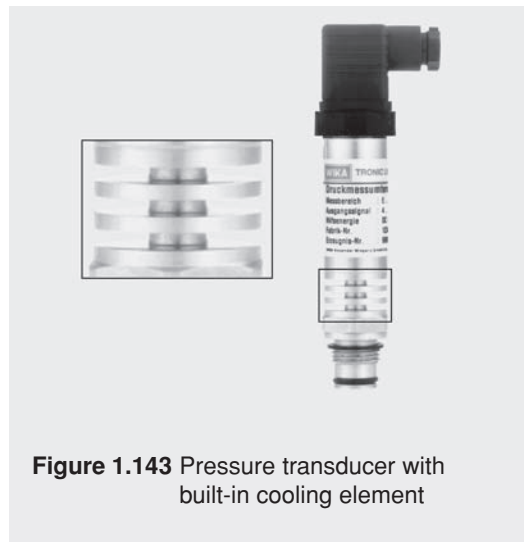
Figure 1.143 Pressure transducer with built-in cooling element

1.5.1.4 Pressure transmitters

Pressure transmitters, a sub-group of pressure transducers, feature additional reset and calibration options. With some sensor types it is possible, for example, to re-set the measuring span over large ranges. This calibration option is usually referred to by such terms as "scale down", "span reset" or "turn down". For instance, a transmitter

with a measuring range of 0 to 400 PSI and a range reset of 1/10 can be calibrated to a measuring range of 0 to 40 PSI while still giving a full output signal (4 to 20 mA, for example).

It is also possible to shift the zero point over a wide range and to calibrate the damping of the output signal between 0 and 32 seconds. Smart transmitters such as Hart®, which also have logging capabilities, can be calibrated, tested and reset via the control desk or hand terminals.

Transmitters are often used in process applications where they can be combined with various chemical seals.

1.5.1.5 Differential pressure transmitter

In differential pressure measurements, two pressures P_1 and P_2 are compared with each other and the difference in pressure is shown as a differential pressure. These measurements are commonly taken using special capacitive differential pressure cells.
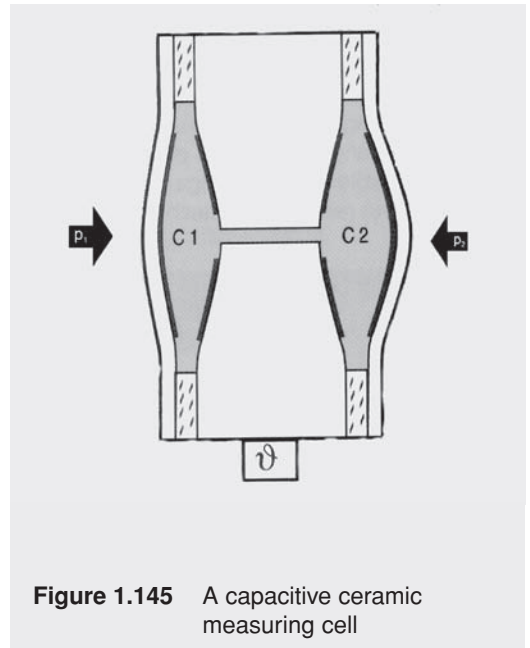
Figure 1.145   A capacitive ceramic measuring cell

This ceramic measuring cell consists of one main ceramic body with two opposing diaphragms that are joined together with a capillary. Each side of the instrument is designed as a capacitive sensor. When pressures P_1 and P_2 are applied, the diaphragms are deflected. If P_1 is bigger than P_2, one diaphragm shifts inwards while the other moves outwards. The differential pressure can be calculated from the resulting deflection.

Figure 1.144 Transmitters with chemical seals
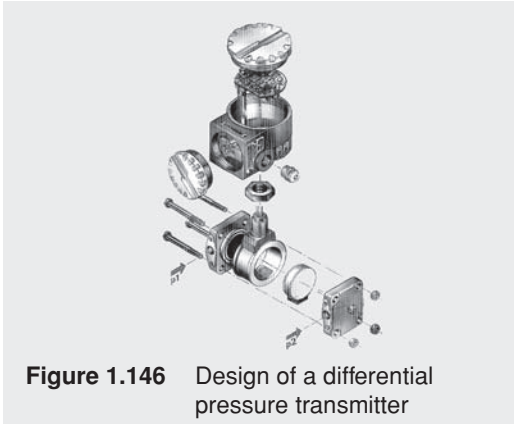
Figure 1.146   Design of a differential pressure transmitter

With capacitive ceramic differential pressure transmitters it is possible to take differential pressure measurements for pressure and vacuum in gases, vapors and liquids.

**Chemical seals
Diaphragm, capsule and
INLINE SEAL™ designs**

WIKA®

1.6 Diaphragm seals

Diaphragm seals transmit the process pressure from the process fluid to the pressure instrument. They are used whenever there should be no contact between the measuring instrument and the process fluid.

The diaphragm seal and the pressure instrument form a complex measuring system whose accuracy depends on many parameters. In order to achieve the optimum configuration of a diaphragm seal / gauge assembly is necessary to have a precise knowledge of the operating conditions. This chapter considers the various difficulties involved in the use of diaphragm seals and provides a general introduction to possible applications.
This information is no replacement for in-depth consultation with manufacturers. It is intended to help prepare for and supplement these discussions.

Applications

There are many possible reasons why a process fluid should be isolated from a measuring instrument:

- the process fluid is highly corrosive. Measuring elements, such as Bourdon tubes, cannot withstand chemical attack.
- the measuring fluid is highly viscous. Unavoidable dead spaces in the gauge or transmitter cause measuring problems.
- the process fluid tends to crystallize, especially in dead spaces.
- the process fluid tends to polymerize. This can cause clogging of the connection lines.
- the process fluid is a slurry. Decomposition and deposits are likely in dead spaces.
- the process fluid is very hot. This can cause the temperature inside the gauge or transmitter to rise to an unacceptable level.
- the process is in a difficult installation location. Installation or reading of the gauge or trans-

mitter is difficult. In this case the instrument is connected to the diaphragm seal by a capillary tube, allowing it to be installed in a more convenient location.
- hygiene regulations must be observed for the process fluid. Bacterial cultures could form at points that are difficult to clean.
- leakage of process fluid to the atmosphere or to the environment is prohibited for safety reasons, environmental protection or risk of radioactive contamination. Adequate measures must be taken to eliminate leaks.
- if a system needs a high overpressure protection, a diaphragm seal with high overpressure safety can be used.

The operating principle behind the diaphragm seal is shown in Figure 1.147.

Figure 1.147 Diaphragm seal with a pressure gauge attached
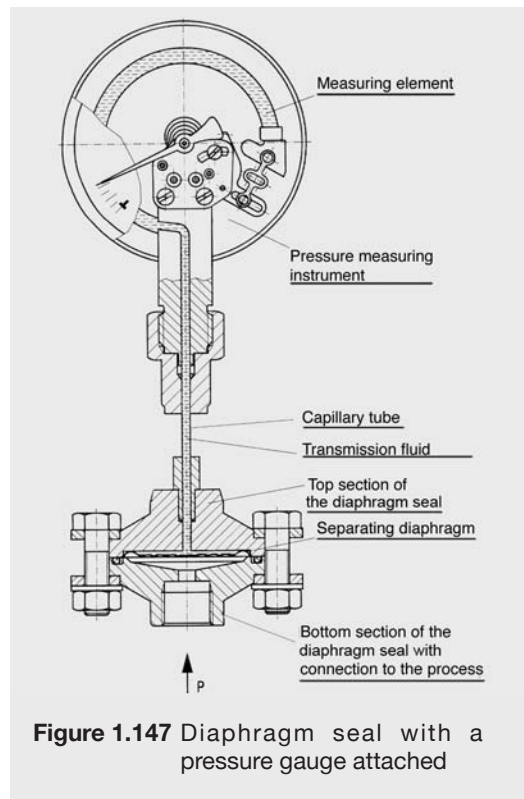
The pressure of the process fluid is hydraulically transmitted to the pressure gauge, switch or transmitter. The process side of the seal is sealed by an flexible diaphragm. The chamber between this diaphragm and the pressure measuring instrument is completely filled with **system fill fluid**. The process fluid pressure is transmitted by the elastic diaphragm into the system fill fluid and from there to the pressure measuring instrument or transmitter.

Sometimes a capillary tube connects the diaphragm seal with the pressure measuring instrument in order to prevent hot process fluids from inducing temperature-related errors in the instrument.

The response time of the system as a whole is affected by the capillary tube. This problem and other influencing factors will be discussed later.

The diaphragm and its connection flange are the parts of the system in contact with the process fluid (wetted parts). Therefore they must be made of a material able to meet the application's requirements in terms of temperature and corrosion resistance. The chemical resistance table (see Section 4.2) gives information on the corrosion characteristics of some materials.

Figure 1.148 Diaphragm seal characteristic

If a leak develops in the diaphragm, the system fill fluid could enter the process media. The system fill fluid must therefore be non-toxic if used in food processing applications. The system fill fluid must also meet a number of other requirements such as temperature range, viscosity, vapor pressure, etc.

Diaphragm seals can be used for "gauge" pressure instruments as well as absolute pressure, differential pressure, switches, transmitter, etc.

The function of a diaphragm seal is directly affected by a number of variable parameters. These must be considered when selecting a diaphragm seal to avoid excessive measuring errors. Correct selection is only possible, however, if the characteristics of the diaphragm seal and their dependence on the influencing parameters are known.

1.6.1 Diaphragm seal characteristic

Deflection of the flexible diaphragm as the result of external pressure was described above. This deflection causes a change of volume of the diaphragm seal chamber above the diaphragm. If the diaphragm seal and capillary tube were not connected to the pressure measuring instrument, the equivalent volume of liquid would leak from the capillary tube at its open end.

The **displacement volume** supplied by the diaphragm seal is needed for the deflection of the measuring element and for the compensation of the volume change in the pressure measuring instrument. In a Bourdon tube gauge, for example, the volume of the tube increases slightly as the radius is increased. The relationship between these changes of volume will be addressed in a later section.

First we address the characteristics of the diaphragm seal itself.

The general relationship between pressure and change in the diaphragm seal is apparent in the displacement volume characteristic illustrated in Figure 1.148.

The characteristic curve shows a linear range defined by the elasticity range of the diaphragm. With further loading beyond its elasticity range, the diaphragm suffers permanent deformation, accompanied by linearity deviations and permanent zero offsets with corresponding measuring errors. Every diaphragm seal is restricted, therefore, to a certain operating range, with an upper limit set to its available working volume.

The characteristic curve can also answer the question of life span. If a diaphragm seal is subjected continually to stress cycles up to its limit of elasticity, i.e. if it is required to supply its maximum displacement volume all the time, its working life will be shortened (Woehler stress-cycle diagram). It makes sense, therefore, to select a diaphragm seal that is not loaded continuously up to its limit of elasticity.

1.6.2 Displacement volume and control volume

The flexible diaphragm seal diaphragm creates the displacement volume. This volume is defined by the diaphragm seal characteristic.

At the same time, every pressure measuring instrument needs a control volume in order to produce a measurable reaction by the measuring element. For example, when a Bourdon tube is exposed to process pressure, it bends open and its volume changes simultaneously. This change of the tube's volume must be compensated by a control volume which needs to be supplied to the measuring instrument from an external source.

If the pressure measuring instrument is connected directly to the process fluid, this fluid provides the necessary control volume. In the case of an intermediate diaphragm seal, on the other hand, the displacement volume must provide the control volume.

The diaphragm seal characteristic must be known, therefore, if you want to select a diaphragm seal with a sufficiently large displacement volume for a pressure measuring instrument chosen for a specific measuring problem.

1.6.3 Practical applications

The displacement volume of the diaphragm seal compared with the volume of the measuring instrument (gauge or transmitter) is affected by other variables in practical applications. Allowances must also be made for changes of volume of the system fill fluid caused by thermal expansion and compressibility. To ensure full compatibility between the diaphragm seal, the capillary line and the pressure measuring instrument, the displacement volume of the diaphragm seal must always be bigger than the sum of the maximum control volume for the instrument and the change of volume of the system fill fluid.

1.6.4 Response time

The response time of a measuring system made up of a diaphragm seal, a capillary tube and a pressure measuring instrument is defined as the time needed by the pointer of the measuring instrument to indicate 90% of the value of a sudden pressure change. This response time depends on the time required for the change of volume of the system fill fluid, for the change of volume of the measuring element, and for the liquid volume to pass through the capillary section.

Since the changes of volume of the system fill fluid are proportional to the total volume, the response time can be improved by reducing the volume of the system fill fluid. As a general rule it is important to optimize the volume of the measuring element, the length and cross section

of the capillary, and the volume of liquid in the diaphragm seal.

In addition to the dimensional data of the measuring system, the temperature-related viscosity of the system fill fluid also influences the response time. So a low-viscosity system fill fluid will reduce response times.

1.6.5 Software-aided selection of diaphragm seals

The quality of a chemical seal measuring system (diaphragm seal, capillary tube and measuring instrument) greatly depends on a combination of various parameters. These include displacement volume, control volume, temperature and pressure-related changes of volume of the system fill fluid, dimensional data of the measuring system, and the characteristics of the liquid under varying operating conditions.

In addition to these complex parameters and their dependence on one another, three fundamental questions must always be answered:

- is the displacement volume of the diaphragm seal adequate?

- what is the measurement error created by temperature and pressure changes?

- what is the response time?

These questions could be answered by "trial and error" using a simple set of the established parameters. Intuition based on experience may even occasionally produce useful answers, but this approach cannot be considered reliable. The optimum configuration for a particular application can only be determined by systematic variation of all the influencing parameters. The iterative solution of the equations for these parameters is an ideal task for a software.

WIKA's solution was to develop its own software program for the optimum configuration of diaphragm seal systems. The data from approximately 40 system fill fluids, more than 50 diaphragm seal models and all the most popular pressure gauges, pressure transducers and transmitters are saved in this program.

The values calculated by the software are the most reliable when accurate operating condition data is input into the system. So, a questionnaire was created for collecting the application-specific data, such as measuring range, ambient temperatures and maximum acceptable response time.

This input data, which differs from application to application, is supplemented by further parameters. The WIKA software also considers parameters as the density, viscosity, thermal coefficient of expansion, compressibility factor and vapor pressure values of system fill fluids, plus the characteristic curves of diaphragm seals and diaphragm shape, diameter, height differentials, etc.

The large number of parameters and their various effects creates a large variety of diaphragm seal system configurations. Therefore, no attempt has been made here to illustrate these effects graphically.

1.6.6 WIKA diaphragm seal systems
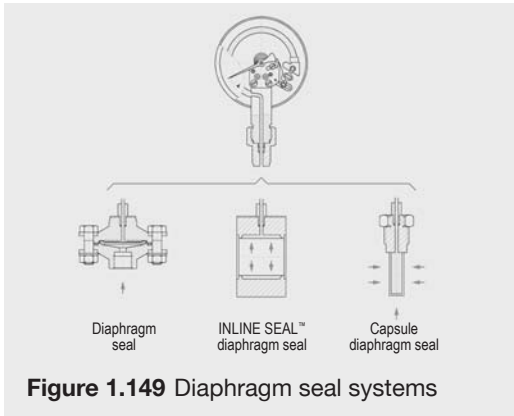
Figure 1.149 Diaphragm seal systems

Since the diaphragm seal must meet various requirements, more than one design is necessary. Several designs have shown particular advantages for certain applications. Today we find three basic types:

1) Diaphragm seals
2) INLINE SEAL™ diaphragm seals
3) Capsule diaphragm seals.

The decision to use a particular type of diaphragm seal depends on the technical data, the installation conditions and the requirements of the specific measuring application.
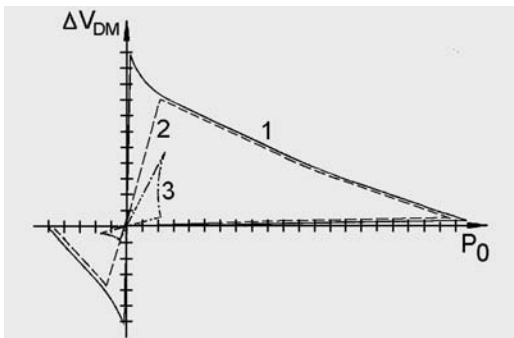
Figure 1.150 Typical diaphragm characteristics fields of the various diaphragm seal systems

The differences in characteristics can be seen in Figure 1.150, where the characteristic curves of a typical representative from each of the three groups (diaphragm[1], INLINE SEAL™ [2] and capsule[3] diaphragm seal) are shown.

The characteristics give a quick overview to select a specific type of diaphragm seal.

The final decision, however, must be based on knowledge of the particular application. Since there are so many applications, it is impossible to draw up a list of schematic selection criteria. Therefore selection of the correct diaphragm seal should be discussed with an expert who has many years of experience.

1.6.6.1 Diaphragm seals

Threaded connections

The standard design of a diaphragm seal is made with a female or male thread for retrofitting to existing threaded ports.

Versions with an open connection flange are available in assorted widths for mating to all standard ANSI and DIN flanges. Their advantage is that the process fluid can act on a larger area of the diaphragm and undesirable "dead spaces" are prevented.
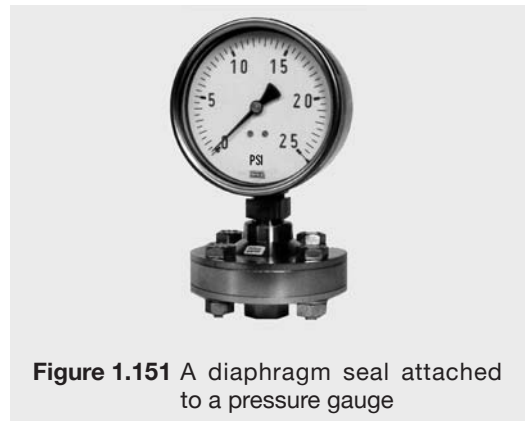
Figure 1.151 A diaphragm seal attached to a pressure gauge
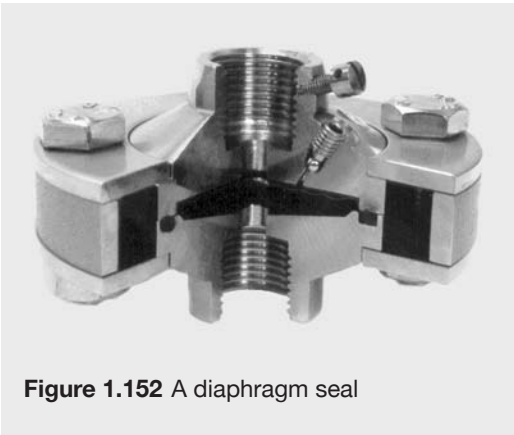
Figure 1.152 A diaphragm seal

Flanged connections

A variation of the standard version is the diaphragm seal with flange. It consists essentially of a flange whose connection dimensions are made to match standardized flange patterns. At the center of the flange is the diaphragm seal diaphragm, which is flush-mounted to the seal section. The flange-type diaphragm seal is installed in place of a blind flange to take pressure measurements.

Pancake connections

A further variation is the pancake diaphragm seal. It consists of a cylindrical plate, whose diameter is adapted to the sealing face section of the respective standardized flanges. The diaphragm seal diaphragm at the center is adapted to its width and lies flush with the front.

The pancake diaphragm seal is fitted to the tapping flange with a backing flange.

Diaphragm-type with extended Diaphragm

Diaphragm-type seals find application on thick-walled and/or insulated product lines, container walls, etc. In their design they resemble flange-type and pancake diaphragm seals and are

installed in a similar manner. They differ in that the diaphragm is positioned on a tube, whose length varies with the thickness of the enclosure, insulation and walls. Therefore the diaphragm is flush with the container internal wall.

Diaphragm seals can be used to monitor pressures of up to 9,000PSI. Their temperature limit is approximately +750°C (+ 400 °C).

1.6.6.2 INLINE SEAL™ diaphragm seals

The INLINE SEAL™ diaphragm seal is ideal for use with flowing and high-viscosity process fluids. Since the in-line diaphragm seal is completely integrated into the process line, any turbulence, corners, dead spaces or other obstructions in flow direction is minimized and does not affect measurements. The process fluid flows freely and cleans the measuring chamber automatically.

This type of diaphragm seal is made up of a thin-walled tube with a circular cross-section that is welded in a cylindrical housing.

The INLINE SEAL™ diaphragm seal is installed directly in the pipeline between two flanges. There is no need, therefore, to make any special connections for the measurements. A variety of standard widths allows adaptation to the cross-section of the particular pipeline.

The maximum pressure range is 6,000 PSI. The temperature limit is approx. +750°F (+ 400 °C).

Figure 1.15 INLINE SEAL™ diaphragm seal

1.6.6.3 Capsule diaphragm seals

The capsule seal is particularly well suited for flowing, slurry process fluids because it is inserted directly into the medium. Compared with other diaphragm seals, it requires very little room. Pressure measurements are taken at a specific point in the piping. The capsule seal consists of an oval tube, which is closed on the one side and acts as the pressure sensor, and a connector that is welded to the tube. A support is incorporated in the sensor to give it rigidity. Internal or external threads are used to thread the diaphragm seal to process piping. The maximum pressure range is up to 20,000 psi and the normal temperature limit is about 752°F (+ 400 °C).

Figure 1.154 Capsule diaphragm seal

The durability and accuracy of pressure measuring instruments with diaphragm seals depend greatly on choosing the right material for the diaphragm and the using a suitable system fill fluid.

A large variety of coated, lined and metal diaphragm materials are available for compatibility with nearly any process medium.

Elasticity and therefore durability depend greatly on the shape of the diaphragm.

Compatibility of the system fill fluid with the particular application is important to help achieve a high level of measuring accuracy. Here again WIKA offers a large selection of system fill fluids from which to chose.

1.6.7 Summary

Many pressure measuring applications cannot be solved without the use of diaphragm seals. The diaphragm seal and the pressure gauge, switch or transmitter form a complex measuring system whose accuracy is affected by many factors.

To design the best possible diaphragm seal to solve a particular measuring application, it is vital to choose a reliable partner with the necessary facilities and, even more important, with the right technical capabilities.
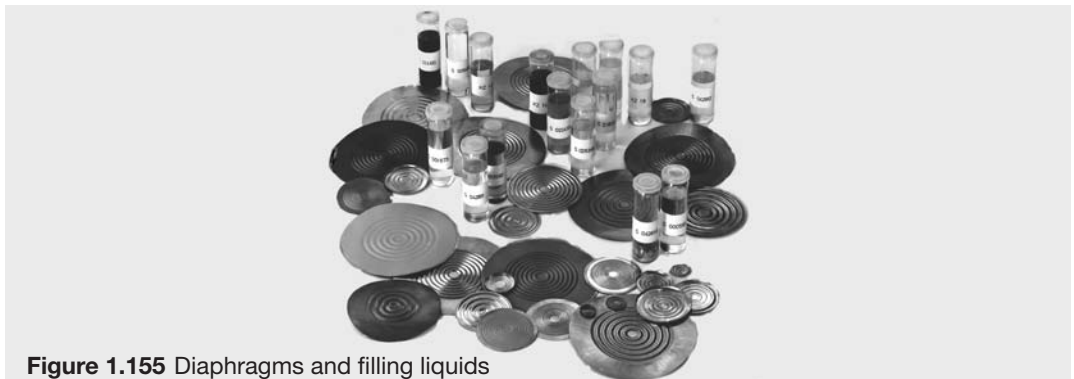
Figure 1.155 Diaphragms and filling liquids

1.7   Selection, installation and initial operation

1.7.1 Checklist for selecting a pressure measuring instrument

1. Pressure

Type of pressure
• Absolute pressure
• Pressure difference / static pressure
• Gauge pressure
• Units of pressure

Level of pressure
• Measuring principle
• Measuring ranges
• Loadability
• Overload pressure
• Bursting pressure

Time response
• Static
• Dynamic
• Pressure peaks

Damping and useful life
• Natural frequency and resonance
• Measuring line
• Restrictor
• Case filling

2. Output of measurement results

Indicator
• Dial / pointer
• Mark pointer
• Drag pointer
• Analog indicator
• Digital indicator

Power supply
• Voltage supply (stabilized/unstabilized)
• Current supply (stabilized/unstabilized)

Electrical accessories
• Magnetically-assisted alarm contacts
• Inductive proximity switches
• Optional accessories

Electrical analog outputs and types of signal
• Variable resistance
• Voltage output
• Current output
• Frequency output
• Digital output

3. Measurement goal

Application
• Monitoring instrument (indicator)
• Industrial measuring instrument
• Precision measuring instrument

Accuracy / error limits
• Error limits
• Hysteresis
• Reproducibility
• Long-term stability

Nominal values
• Sensitivity
• Reading distance

Influencing factors
• Effect of temperature
• Variation due to position
• Effect of frequency / waveform of the indication
• Density of process fluid
• Ventilation of the measuring chamber
• System filling
• Electromagnetic radiation (EMC)

4. Type of process fluid

State of medium
• Gaseous
• Liquid
• Changeable, solid - liquid
• Suspended particles (abrasive)

Chemical properties
• Corrosion
• Reactive (i.e. oxygen)
• Toxic, hazardous
• Radioactive
• Hygiene requirements (cleaning, sterilization)

Diffusion
• Material brittleness
• Subsurface corrosion
• Pressure build-up in filled measuring chambers

Temperature
• Process fluid temperature
• Bonding technology and materials
• Temperature coefficients

Safety requirements
• Solid front design
• Protected for use in explosive atmospheres

5. Mounting and installation conditions

Type of connection
• Threaded type connection
• Flange type connection

Connection position
• Lower mount
• Back mount
• Special positions

Installation position
• Upright
• Suspended
• Horizontal

Types of mounting
• Direct connection (tube type connection)
• Panel mounting
• Wall mounting

6. Operating conditions

Climate
• Temperature
• Protection from water / dust
• Moisture
• Atmospheric pressure
• Corrosion

Vibration, shock
• In transit
• In use

Radiation
• Thermal radiation
• UV radiation
• Radioactive radiation
• Electromagnetic radiation (EMC)

7. Directives, regulations, certifications

Regulations concerning safety
• Government safety regulations
• Accident prevention guidelines
• Other safety rules

Test reports and certificates
regarding: Material properties
              Pressure resistance
              and tolerances
              Accuracy
issued by: Company experts or
              indepenent experts

Certificate of Compliance

Certificate of Calibration

Material Certificate

1.7.2 Installation and operating instructions for pressure measuring instruments

Pressure measuring instruments must be installed in such a way that they are unaffected by vibrations and their readings are easy to see.

A shut-off device is recommended between the pressure tapping point and the pressure measuring instrument so that the measuring instrument can be replaced and zero checks made while the system is in operation.

1.7.2.1 Accessories for the measuring point and attachments for pressure measuring instruments

In many cases, pressure gauges accessories are necessary for proper, safe installation of the pressure measuring instrument.

Special attention is given to the chemical seal due to its growing importance and because its use is not limited to just pressure measuring instruments with a flexible measuring element. In conjunction with pressure and differential pressure transmitters, it has become an indispensable protective device for pressure measurement applications in the process industry.
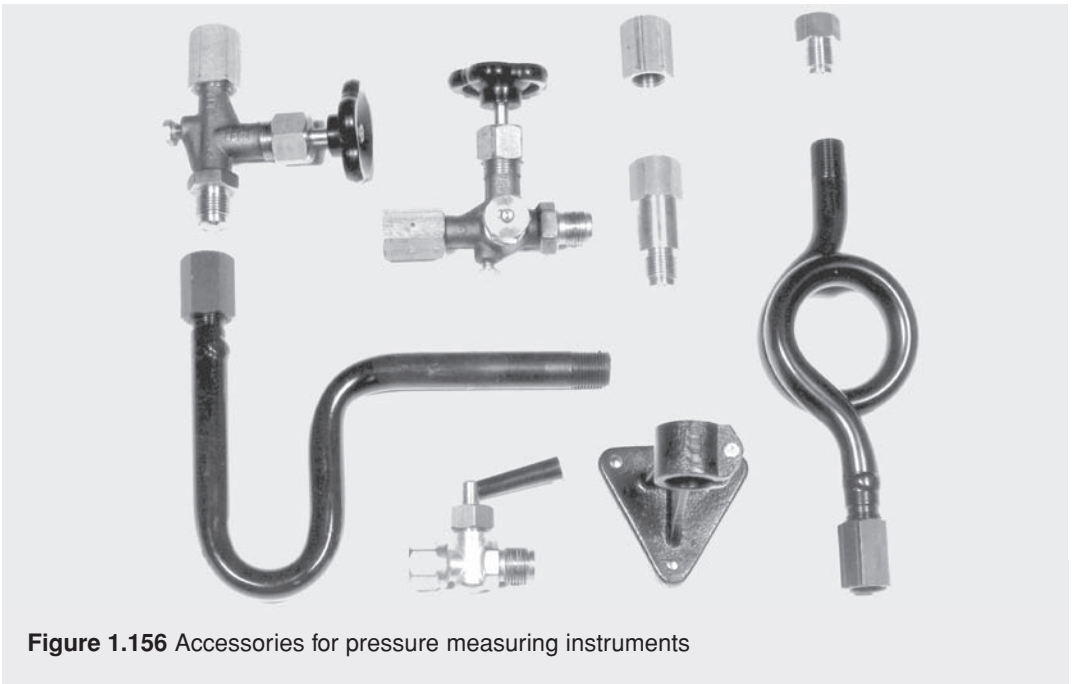
Figure 1.156 Accessories for pressure measuring instruments

1.7.2.2 Shut-off devices

For certain applications it is common to install stopcocks or shut-off valves upstream from the pressure measuring instrument.

Stopcocks have three settings:

Ventilation   The supply line is closed and the measuring system is connected to the atmosphere. The zero point can be checked.

Operation   The supply line is open. The measuring system is under pressure.

Blow-out   The supply line is open. The process medium escapes into the atmosphere. The measuring system is not in operation.

Shut-off valves have a ventilation screw between the valve seat and the pressure instrument connection. Ventilation holes must be positioned where employees are not in any danger from escaping process media. Environmental pollution must be prevented.

For certain applications, such as steam boilers, the shut-off devices must have a test connection to allow the pressure measuring instrument to be checked without dismantling the instrument.

1.7.2.3 Mounting the measuring instrument into position

If the line to the measuring instrument is not isolated from vibration, it is necessary to use either a special instrument bracket or additional fasteners around the edge of the case.

1.7.2.4 Damping the measuring system

If it is not possible to isolate the instrument from vibrations with special fittings, the instrument should be used with a liquid filling.

1.7.2.5 Temperature considerations

Pressure measuring instruments should be installed so that it is within its designed operating temperature range, including the effects of convection and thermal radiation. Adequately long measuring lines or siphons should be used to protect the pressure measuring instrument and shut-off valve or stopcock.
Temperature has an effect on the reading accuracy of pressure measuring instruments, and these effects must be considered.

1.7.2.6 Chemical seals / protective buffers

Chemical seals should be used as protective buffers when working with aggressive, hot, highly viscous, contaminated or crystallizing process media that cannot enter the measuring system. The pressure is then transferred to the measuring system by a neutral liquid, which must be chosen in consideration of the particular measuring range, temperature and compatibility with the process fluid. The connection between the pressure measuring instrument and the chemical seal must never be disassembled.

1.7.2.7 Protective devices

If the process fluid is subject to rapid changes of pressure or if pressure spikes are likely, they must not be allowed to act directly on the measuring system. Appropriate throttling devices, such as a built-in throttling line or an adjustable upstream restrictor, must be used to reduce the impact of these changes.

If, for operating reasons, the indicating range needs to be smaller than the maximum system pressure, the pressure instrument can be protected from damage by connecting an upstream overpressure protection device.

The overpressure protection device closes immediately when there is a sudden pressure surge, and gradually when there is a slow rise in pressure. The actual closing pressure depends, therefore, on the time-related pressure characteristic.

1.7.2.8 Measuring arrangements
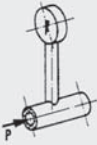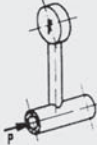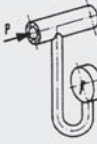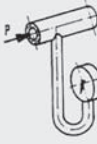
	liquid process fluids			gaseous process fluids		
Filling of the measuring line	liquid	partly gaseous	completely evaporated	gaseous	partly condensed (moist)	completely condensed
Examples	condensate	boiling liquids	liquid gases	dry air	moist air flue gases	water vapor
Pressure measuring instrument above tapping leg						
Pressure measuring instrument below tapping leg						

Figure 1.157 Recommended installation configurations for various types of process fluid

The pressure tapping leg should have a sufficiently large hole (at least 1/4 inch) and be designed, if possible, with a shut-off valve or stopcock so that the pressure measurement is not disrupted by currents in the process fluid. The internal diameter of the measuring line between the pressure tapping leg and the pressure measuring instrument should be big enough to eliminate clogging and delays in the pressure transmission. It should have no sharp bends and be installed with a recommended gradient of approximately 1:15.

The measuring line must be designed and installed so that it can absorb the loads resulting from strain, vibrations and heat.

When gases are the process medium, there should be a drain hole (weep hole) at the lowest point. With liquid process media there should be an air vent at the highest point.

If the gas or liquid medium contains solid particles, the measuring line must contain traps that can be separated from the rest of the system by shut-off valves and emptied during operation.

If the measuring instrument has to be installed higher or lower than the tapping point, there will be a shift in the measuring range if the process fluid in the measuring line does not have the same density as the ambient air.

The reading will drop if the pressure measuring instrument is installed on a higher level and will rise if installed on a lower level than the pressure tapping point (see Section 1.4.7.9).

The pressure measuring instrument should be installed in an upright position for easy readability.

1.7.2.9 Installation and start-up

The pressure measuring instrument must be installed so that the connection threads are completely sealed. Use of Teflon tape is recommend for NPT threads, and sealing washers are necessary for metric straight threads.

Pressure measuring instruments should be threaded or unthreaded by using the wrench flats on the socket. Never apply torque to the cases to install the instruments.

If the pressure measuring instrument is in a lower position than the pressure tapping leg, the measuring line must be flushed thoroughly before the connection is made in order to remove any foreign matter.

The pressure used to blow out pipelines or vessels must not exert a greater load on the pressure measuring instrument than the pressure rating of the gauge. If the pressure is too high, the pressure measuring instrument must be either shut-off or removed.

With diaphragm or capsule pressure measuring instruments, the clamping screws on the top and bottom flange must not be removed.

Pressure fluid remnants in pressure measuring instruments removed from service can be a source of danger to personnel, the environment and equipment. It is essential to take suitable precautions.

Pressure measuring instruments with a measuring system filled with water or a water mixture must be prevented from freezing.

1.7.2.10 Operation

Shut-off devices are to be opened slowly in order to prevent pressure surges.

The pressure measuring instrument should not be exposed to pressures higher than its rating which is typically two-thirds of its full scale pressure for static loads, and 75% of its full scale pressure for alternating loads.

The shut-off device must be closed and the measuring system vented for zero checks during operation. The pointer must then lie inside the zero box, or on the stop pin if so equipped.

If the pointer lies outside the zero box or above the stop pin, it can generally be assumed that the measuring element has suffered permanent deformation. The measuring element must be examined closely in order to eliminate measuring errors or accidents.

To check readings during operation, the pressure measuring instrument must be isolated using a shut-off device with a test connection and then loaded with test pressure.

1.7.2.11 Storage

To prevent damage to pressure measuring instruments while they are being stored prior to installation, the following points should be observed

- leave the pressure measuring instruments in their original packaging.

- if the measuring instruments are removed temporarily (i.e. for inspection), they must then be put back in their original packaging.

- note the storage temperature limits quoted on the respective data sheets. Storage temperatures may well differ for different types of measuring instrument. Consult the respective data sheet for the acceptable temperature range.

- protect the measuring instruments from moisture and dust.

1.7.2.12 Hazardous process fluids

The specific regulations regarding hazardous process fluids such as
oxygen,
acetylene,
combustible substances or
toxic substances
and for refrigeration systems, compressors, etc. must be followed in addition to the general regulations.

1.7.3 Certification and testing

1.7.3.1 Certification of material tests

Pressure measuring instruments for special applications (most notably nuclear installations) must meet strict requirements: special tests must be carried out on their wetted components, specific production regulations must be met, and exact records of the chemical and physical properties of their materials must be documented. The results of these tests can be put into a special material certification document.

Two forms of material certification are available.

Type 2 - Material testing performed and documented by the manufacturing or processing factory.

Type 3 - Material testing performed and documented by an agency independent of the manufacturing or processing factory

In addition to material certificates other testing, such as to verify other typical properties that are determinable by testing (i.e. tolerances or pressure resistances), are available.

The following table lists the standard certificates and their use at WIKA.

1.7.3.2 Calibration

In view of the growing importance of instrument calibration, especially in connection with certified quality assurance systems in accordance with DIN ISO 9001, we shall give this subject special attention in Section 3.2.

Types of WIKA Certificates

Certificate	Issued by	Content
Certificate of Compliance	WIKA Quality Assurance	Certifies that the order complies with the data sheet specifications current at the time of ordering.
Certificate of Inspection	WIKA Quality Assurance	Inspection certificate showing the instrument has been tested at a pre-set number of calibration points and met the accuracy standards listed on the data sheet current at the time of ordering.
Material Certificate (DIN 3.1B)	WIKA Quality Assurance	Certifies that the material composition of the wetted parts of the instrument have been tested to ensure they meet or exceed the data sheet specifications current at the time of ordering.
Material Certificate (DIN 3.1C)	Independent testing laboratory	Certifies that the material composition of the wetted parts of the instrument have been tested by representatives independent from the factory to ensure they meet or exceed the data sheet specifications current at the time of ordering.

Certificate of Compliance

Certificate of Calibration

Material Inspection Certificate
(3.1 B)

Temperature measuring instruments, electronic analog and digital temperature transmitters

WIKA®

2 Thermometry

2.1 Introduction to thermometry

In the same way that the boy playing with a paper streamer (Figure 1.50) unconsciously learns about the physical quantity "pressure", temperature is a quantity that can be readily perceived by the human senses, by contact with the skin or by visually by eye. The concepts "warm", "cold", "ice cold" or at high temperatures "red hot" or "white hot" are familiar to everyone. Human beings are quite good at comprehending temperature differences, whether something is colder or warmer than another substance or object. However, the determination of an exact temperature is outside man's abilities. In technical measurements temperature can be determined by the material properties dependent on it. It is again necessary to rely on comparison of the thermal change detected at the measuring equipment with a known reference point, i.e. the temperature of melting ice, to allow its quantitative evaluation. Basically, all properties which can be influenced by temperature, such as the expansion behavior of gases, liquids and solid substances, the electrical resistance of metal conductors, the current flow through metal conductors, the current flow through a semiconductor, the radiation density of glowing materials, the resonant frequency of an oscillating crystal, etc. can be used for temperature measurement.

Temperature plays an important role in the reproducibility of product quality, the profitability of production processes and the operational reliability of industrial installations and equipment. Besides pressure it is the most frequently measured physical quantity in technology. In industrial production processes the temperatures that are commonly measured are usually between -450°F (-273 °C) and about 6000°F (3500 °C), but can reach substantially higher ranges in special processes. Temperatures even higher than 100 million°F occur in plasmas.

Measuring equipment or instruments, in which the input quantity is the temperature and the output signal is proportional to the temperature, are called thermometers. A temperature sensor can also be considered to be a thermometer if it is a self-contained unit and supplies a temperature-dependent output signal, which can then be further processed by other measuring instruments. Many temperature measuring methods and equipment (thermometers) have been developed for the most diverse measuring tasks in research and technology in consideration of the required field of application, the required measuring accuracy and the specific installation and process conditions.

The methods can basically be subdivided into contact and non-contact temperature measuring methods. In contact temperature measuring methods the thermometer, and in particular the part containing the temperature-sensitive sensor, is brought into thermal contact with the measured medium at the area of installation. The energy exchange between thermometer and measured medium takes place primarily via thermal conduction. Both must be in thermal equilibrium at the time of temperature measurement. The most important contact temperature measuring methods, industrial thermometer types and typical applications for these measuring instruments are described below.

Non-contact temperature measuring methods use the energy exchange between measured object and thermometer by heat radiation. They are not described in greater detail here. Literature references are given for further information on this field of industrial thermometry.

The industry requirements on thermometry vary widely because of the diversity of the processes in which it is used. The thermometer must meet the specific process requirements in consideration of the field of application, the measuring range and its time response. Industrial users expect repeatability of the measurement results with high measurement accuracies. They require rugged, easily applied technical solutions with low installation and operating costs.

For many users the motto "install and forget" stands for the expectation that the life of the installed thermometer corresponds to the life of the entire plant.

Process automation is creating a great demand for thermometers which supply an output signal capable of long-distance transmission. A prerequisite is national or international comparability of the measurement results to allow the same production quality regardless of location.

Low failure rates and high process reliability require thermometer designs according to the valid standards and specifications for electromagnetic compatibility, explosion protection, type of protection, health and fire protection and environmental compatibility.

2.1.1 Historical development of the thermometer

The history of temperature measurement dates back to the beginnings of the modern development of natural sciences. The first physical thermometer, the thermoscope, was used by Galileo at the end of the 16th century. He immersed a glass tube closed at one end in a vessel filled with water or spirits. The height of the liquid in the glass tube depended on the temperature of the trapped air. But, the atmospheric pressure adversely affected this measuring instrument.

The first liquid glass thermometers independent of atmospheric pressure were introduced early in the 17th century by Grand Duke Ferdinand II of Tuscany. These glass thermometers filled with alcohol began a period of rapid development.
The scales of the so-called "Florentine thermometers" were adapted to each other by comparison. The temperature of the coldest snow was taken as 20°F and the highest summer temperature as 80°F.

In 1664 Robert Hooke made the first attempt to establish a generally valid temperature scale with the aid of the liquid glass thermometer. Various thermometers were calibrated against a standard thermometer.

The Italian Renaldini, who calibrated the thermometer on the freezing and boiling point of water, and in particular the Danzig glass blower Fahrenheit (1724), who succeeded in producing highly accurate thermometers in the form still used today with mercury as thermometric liquid, helped to establish the concept of a temperature scale independent of a reference thermometer.

The first developments of the spring thermometer date back to 1879, when F. Wiske developed the gas spring thermometer with a plate and tube spring, P. Grüdelbach the mercury spring thermometer and J.W. Klinghammer the vapor pressure spring thermometer. The liquid spring thermometer with a capillary tube still in use today was designed in 1882. The first simple bimetallic thermometers were developed by A.L. Breguet around 1800.

The measurable temperature range of liquid glass thermometers was extended by the development of electrical thermometers. The dependence of the electrical resistance of pure metals on temperature was used by Sir William Siemens in 1871 for his platinum thermometer, which was developed 14 years later by H.L. Callendar into a precision thermometer for higher temperatures by adding special protective measures.

On the basis of the phenomenon of thermoelasticity described by Seebeck in 1821 thermocouples suitable for temperature measurement were developed at a relatively late stage in 1887 by H. le Chatelier and in 1889 by C. Barus.
An important extension of the measurable temperature range towards much higher temperatures was made with the development of radiation thermometers. The first usable spectral pyrometers were made by H. le Chatelier in 1892 and

improved a few years later by Ch. Fèry. At the turn of the century H. Wanner introduced a thermometer based on the principle of a polarization photometer. The development of the disappearing-filament pyrometer, with which it was possible to directly observe the measured object, is attributed to L. Holborn and F. Kurlbaum. The concave mirror pyrometer with a bimetal as radiation receiver was likewise developed by Ch. Fèry. A pyrometer, in which the sensor element consisted of thin wires (bolometer), which change their electrical resistance with the irradiation, was designed by Hirschsohn-Braun. A lens pyrometer, the temperature indication of which was largely independent of the distance between measured object and radiation receiver, was finally achieved with the ardometer of Siemens & Halske.

2.1.2 Historical development of the temperature scales

The need for reliable temperature scales as a prerequisite for clear measurement results was already recognized in the early stages of thermometer development. Therefore efforts were made to calibrate the thermometers on reference points with good reproducibility. Since it was easy to determine the freezing point and boiling point of water at the time, these reference points were quickly used for these purposes (Renaldini 1694).

In his temperature scale Fahrenheit assigned the value 0°F to the temperature of a salt-ammonia freezing solution, 32°F to the temperature of melting ice and +92°F to the body temperature of a healthy person. In the temperature scale devised by Réaumur around the same time 32°F is assigned to the freezing point and 176°F to the boiling point of water. The 100°C (212°F) graduation of the temperature scale between freezing and boiling water was proposed for the first time by the Swedish astronomer Celsius in 1742. In the temperature scale named after him and still in use today, Celsius ironically assigned 0°C to the boiling point of water and 100°C to the freezing point.

Eight years later his compatriot Strömer introduced the "Celsius scale" with the current assignment of 0°C to the freezing point and 100°C to the boiling point.

With the thermodynamic temperature scale Lord Kelvin created an easily reproducible scale independent of all substance properties and the temperature level in 1852. This temperature scale based on the second law of thermodynamics is of fundamental importance for definition of the physical quantity "temperature" and its unit, the Kelvin. It is described in more detail in Section 2.2.1.

Since the gas thermometer measuring methods generally used for determining the thermodynamic temperature are extremely difficult to use and technically complicated, a practical temperature scale was established on the basis of international agreements.

This International Temperature Scale (ITS) is based on a selected number of easily reproducible physical equilibrium temperatures, so-called reference points, to which defined values are assigned on the basis of highly accurate measurements. Interpolation and extrapolation formulae for electrical thermometers, which reproduce the relationship between the temperature of the reference points and the indication of these instruments, if they have been calibrated at the corresponding reference points, are set up for the range between these reference points. The International Temperature Scale is specified by the "Comité International des Poids et Mésures" in Europe. It does not replace the Thermodynamic Temperature Scale, but approximates to it in the best possible way according to the state of thermometry under practical considerations.

In 1927 the ITS-27 was introduced as the first International Temperature Scale providing a common basis for scientific and industrial temperature measurements. It was replaced in 1948 by the IPTS-48 (International Practical Temperature Scale) and further improved in 1960. More accurate gas thermometer measurements sometimes revealed considerable deviations between the scale values set in IPTS-48 and the thermodynamic temperature. In addition, the valid temperature scale was extended towards lower temperatures with the aid of improved thermometers and measuring methods. Therefore the European International Committee for Weights and Measures drew up the International Practical Temperature Scale as IPTS-68 in 1968. This IPTS-68 was based on 13 reference points. It extended the temperature scale down to 13.1 K (Kelvin). All reference points were determined by accurate gas thermometer measurements. The IPTS-68 was viewed as an important advance.

2.2 Principles and definitions of temperature measurement

From the physical point of view temperature can be described as a measure of the energy inherent in a body, which results from the unordered movement of its atoms or molecules. Temperature is a state variable, which together with quantities such as mass, heat capacity and others, describes the energy content of a body or system. Therefore temperature could be measured directly in energy units. However, the tradition of specifying the temperature in degrees had already been introduced far earlier and was well established in physics, so that for practical reasons it was not reasonable to discontinue the use of degrees.

If a body no longer possesses heat energy, its molecules are in the state of rest. This state, which cannot exist in reality, is designated absolute zero. Since there is no state with lower energy, the value O K (Kelvin) is assigned to it. The Kelvin

temperature is always a positive quantity according to this convention.

To measure the temperature of an object a scale is needed which can be defined by a reproducible measuring method independent of the properties of the thermometric substance used. The physical properties of liquids and solids are usually highly complex, are not linearly dependent on the temperature and can only be used within a narrow temperature range. So the first temperature scales (see 2.1.2) could only be used to a limited extent.

By contrast the theory of the ideal gas law shows a very simple relationship between temperature, pressure and volume.

$$T = \frac{p \cdot V}{const.} \qquad (2\text{-}1)$$

The hydrogen scale, agreed upon internationally in 1887, was based on this relationship. The limits of this scale became evident as a result of the real gas behavior of the hydrogen and helium used, particularly at very low temperatures. A physically accurate definition of a temperature scale over the full temperature range was first given by the thermodynamic temperature scale.

2.2.1 The thermodynamic temperature scale

The definition of the thermodynamic temperature scale, also known as "Kelvin scale", follows from the second law of thermodynamics. It was accurately defined for the first time with the aid of the thermal cycle proposed by Carnot. In this cycle (Figure 2.1) work is performed by a heat engine operating under ideal and reversible conditions between two heat reservoirs at different temperatures. Starting from a higher temperature T_1 (p,V condition I) the heat quantity Q_1 is supplied to the medium isothermally, i.e. at constant temperature.

Figure 2.1   Carnot cycle

$$1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1} \qquad (2\text{-}4)$$

With a given temperature T_1 the temperature T_2 can be determined in this way

$$T_2 = T_1 \cdot \frac{Q_2}{Q_1} \qquad (2\text{-}5)$$

The temperature and thus the temperature scale is clearly determined theoretically by this equation in the first case. It is designated "thermodynamic" or also "absolute" temperature.

For practical calculation of the thermodynamic temperature, the heat quantities belonging to temperatures T_1 and T_2 must be determined experimentally. This procedure is complicated and in addition is not sufficiently accurate. Starting from the knowledge that thermodynamic temperatures can basically be measured with any measuring method, which can be derived from the 2nd law of thermodynamics, the thermodynamic temperatures are currently measured with a gas thermometer, the spectral pyrometer, the total radiation pyrometer or other suitable measuring instruments in meteorological practice. Table 2.1 shows measuring methods, which are used to establish the temperature scale because of their small measuring uncertainties.

In the p,V diagram the condition II is achieved. The medium is subsequently converted into condition III adiabatically, i.e. without heat exchange with the environment, with performance of work. The temperature falls to T_2. The heat quantity Q_2 is now removed from the medium again at constant temperature and transferred into the second heat reservoir. The system is finally restored to the initial condition by adiabatic compression. The work performed in this cycle is given by the difference between the two heat quantities.

$$W = Q_1 - Q_2 \qquad (2\text{-}2)$$

The thermal efficiency of the heat engine is independent of the selected medium and is ultimately only a function of the two temperatures T_1 and T_2.

$$\eta = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = \frac{T_1 - T_2}{T_1} \qquad (2\text{-}3)$$

Method	Physical principle	Measuring range [K]	Uncertainty [mK]
Gas thermometer	ideal gas behavior	2.4 to 700	0.3 to 15
Acoustic thermometer	sound velocity in the ideal gas	2 to 20	0.3 to 1
Thermal noise thermometer	noise of an electrical resistance	3 to 1100	0.3 to 100
Spectral pyrometer	spectral radiation density of a cavity radiator	700 to 2500	10 to 2000
Total radiation pyrometer	total radiation of a cavity radiator	220 to 420	0.5 to 2

Table 2.1   Measuring methods for measurement of thermodynamic temperatures

2.2.2 Temperature and its units

Since the zero point of the thermodynamic temperature scale is already physically established, it is sufficient to define the temperature unit as a specific part of a clearly established thermodynamic temperature.

The unit of the physical basic quantity "thermodynamic temperature" denoted by T is the Kelvin with the symbol K, which is defined as a 273.16th of the thermodynamic temperature of the triple point of water.

$$1 \text{ K} = T_{tr}/273,16 \rightarrow T_{tr} = 273.16 \text{ K} \qquad (2\text{-}6)$$

This definition was adopted at the 13th General Conference on Weights and Measures (1967/68). The prefix "basic" characterizes the temperature as one of the seven basic quantities of the International System of Units (SI). "Thermodynamic" in this case marks the temperature as a fundamental quantity in physics. As already mentioned in Section 2.1, there is an internationally agreed temperature scale in addition to the "thermodynamic" temperature. It is dealt with as International Temperature Scale 1990 (ITS-90) in Section 2.2.3.

The triple point of water is the only thermodynamic condition in which the three phases of the water liquid, vapor and solid, are in equilibrium. As long as all three phases are present, pressure and temperature remain constant. This triple point can now be determined with very small measuring uncertainties. The numerical value 273.16 K is assigned to this reference point by agreement.

The arbitrary specification of this numerical value has a historical reason dating back to 1954. The newly defined temperature unit most closely agreed with the previously valid Kelvin (K) temperature. It was defined as the 100th part of the temperature difference between the boiling point (373.15 K) and the melting point of water (273.15 K).

The Celsius temperature designated "t" is defined by the equation:

$$t = T - 273.15 \text{ K} \qquad (2\text{-}7)$$

i.e. via a temperature difference. Its unit is the degree Celsius designated by °C. The unit °C is identical in magnitude with the unit Kelvin. The

zero point of the Celsius scale is 0.01 K below the triple point of water by agreement. In the Celsius scale temperatures greater than 273.15 K are specified with a plus sign. Instead of the symbol "t" the letter "ϑ" can be used when there is a risk of confusion with the basic quantity "time". The temperature differences can be specified in °C or K.

In the United States temperature is specified in degrees Fahrenheit (°F). The temperature values in the thermodynamic temperature scale corresponding to the degrees Fahrenheit are expressed in Rankine degrees (°R).

The relationship between the temperature units can be specified as follows:

$$1 \text{ K} \triangleq 1°\text{C} = \frac{9}{5} \ °\text{F} \qquad (2\text{-}8)$$

The following equations apply to the conversion of the numerical values of temperatures in the Celsius (t_c), Kelvin (T_k), Fahrenheit (t_F) and Rankine scale (T_R):

$$T_K = 273.15 + t_C = \frac{5}{9} \ T_R \qquad (2\text{-}9)$$

$$t_C = \frac{5}{9} \ (t_F - 32) = T_K - 273.15 \qquad (2\text{-}10)$$

$$T_R = 459.67 + t_F = 1.8 \ T_K \qquad (2\text{-}11)$$

$$t_F = 1.8 \ t_C + 32 = T_R - 459.67 \qquad (2\text{-}12)$$

2.2.3 The International Temperature Scale (ITS-90)

The International Temperature Scale, ITS-90 for short, is the temperature scale established in Europe by law since Jan. 1, 1990. It was based on international agreements and includes the latest findings in science and research. The ITS-90 extends from 0.65 K to the highest temperatures currently measurable on the basis of Planck's radiation law.

Compared to the ITS-68 valid until Dec. 31, 1989 it is in substantially better agreement with the thermodynamic temperatures because of the reduction in modern measuring uncertainties. For example, the platinum-rhodium (10% rhodium)/platinum thermocouple as standard equipment was replaced by the platinum resistance thermometer for the temperature range between 904 K (631°C) and 1234.93 K (961.78°C). The achievable measuring uncertainties were thus reduced from 200 mK to 10 mK. The range of the radiation pyrometer already begins at the silver solidification point (961.78°C). It replaces the thermocouple as standard equipment between 961.78°C and 1064.18°C (solidification point of gold). An advantage important above all for the practical application of the ITS-90 results from the specification of alternative definitions in specific temperature ranges. The predominant use of triple points and solidification points as defining reference points of the temperature scale led to a clear improvement in its reproducibility.

The ITS-90 is based on 17 readily reproducible fixed points (Table 2.2), to which specific temperatures are assigned. The temperature values are mean values of the thermodynamic temperatures determined in various national institutes, which are now regarded as valid optimum values and specified in ITS-90.
The temperatures measured according to ITS-90 are characterized by the subscript 90 (e.g. T_{90} t_{90}).

State of equilibrium	T_{90} in K	t_{90} in °F
Vapor pressure	3 to 5	-454.27 to -450.67
Triple point of equilibrium hydrogen *)	13.8033	-434.8241
Vapor pressure of equilibrium hydrogen *)	∪17 ∪20.3	∪-429.07 ∪-423.13
Triple point of neon	24.5561	-415.4690
Triple point of oxygen	54.3584	-361.8249
Triple point of argon	83.8058	-308.8196
Triple point of mercury	234.3156	-37.9019
Triple point of water	**273.16**	**32.018**
Melting point of gallium	302.9146	85.5763
Solidification point of indium	429.7485	313.8773
Solidification point of tin	505.078	449.470
Solidification point of zinc	692.677	787.149
Solidification point of aluminium	933.473	1220.58
Solidification point of silver	1234.93	1763.20
Solidification point of gold	1337.33	1947.52
Solidification point of copper	1357.77	1984.32

*) Hydrogen occurs in two molecular types designated by the prefixes "ortho" and "para". The composition of the ortho-para mixture prevailing in the state of equilibrium is temperature-dependent. The term "equilibrium hydrogen" means that the hydrogen has its ortho-para equilibrium composition at the respective temperature.

Table 2.2   Defining reference points of ITS-90

Figure 2.2 Schematic representation of the expansion behavior of a substance in the p-T diagram

The **defining reference points** (Table 2.2) are phase equilibria of high-purity substances. They can be made clear with the aid of a P-T diagram, which describes the expansion behavior of a substance (Figure 2.2). The state fields of the solid, liquid and gas exist according to the pressure and temperature.
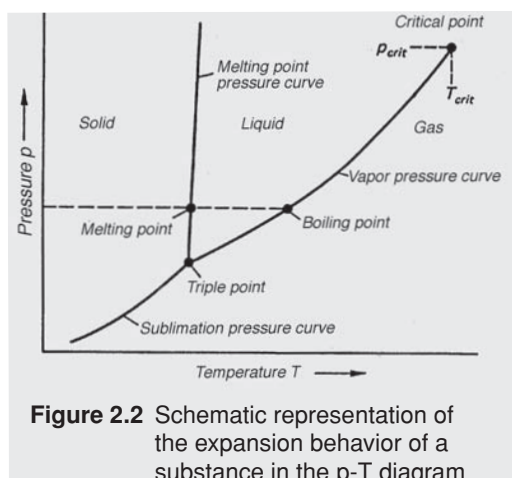
The dividing lines between these areas are formed by the melting point pressure curve, the vapor pressure curve and the so-called sublimation pressure curve. The vapor pressure curve terminates at the critical temperature. At still higher temperatures there are no longer definable limits between the liquid and vapor phase. Therefore liquids and gases are also included under the term fluids. The triple point forms the point of intersection of all three curves. The solid, liquid and gaseous phase of the substance under consideration are in thermodynamic equilibrium at this point.

All other states of equilibrium lie on the vapor pressure curve according to the transition from liquid to gaseous and on the melting point pressure curve from liquid to solid.

States of equilibrium of high-purity metals, water and selected fluids are now used for representation of the temperatures of the international temperature scale. With a few exceptions a high technical input is required for the reproducible realization of the defining fixed points and accurate temperature determination.

The temperatures between the fixed points are measured by standard equipment, which is calibrated at the corresponding fixed points. The tem-
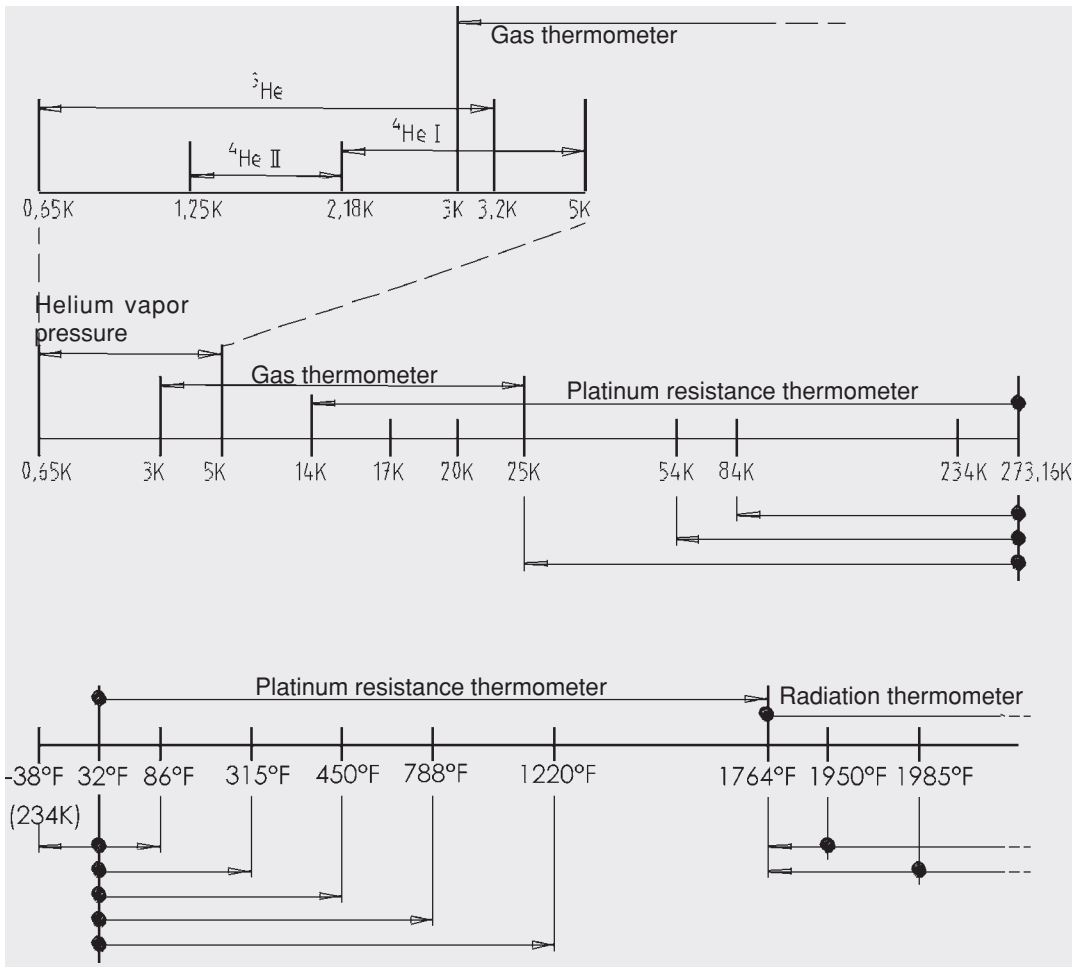
Figure 2.3 Ranges, sub-ranges and interpolation instruments of ITS-90

perature values can be calculated from the indications of this standard equipment with the aid of the definition equations specified for the respective temperature range. The ITS-90 consists of partial ranges and sub-ranges, for which the defining reference points, the standard equipment and the interpolation equations are specified (Figure 2.3). Because of the overlap of some partial ranges several measuring methods or standard instruments can be used for temperature determination.

According to the type of predetermined standard equipment the ITS-90 specifies the temperature range
- from 0.65 K to 24.5561 K
- from 13.8 K to 1234.93 K
- above the silver solidification point (961.78°C). Several equivalent definitions exist from 0.65 K to 24.5561 K. The temperature T_{90} is measured between 0.65 and 5 K with the aid of a Helium vapor pressure thermometer. ^{3}Helium is used as measuring gas for the partial range from 0.65 K to 3.2 K and ^{4}Helium for temperatures from 1.25

to 5 K. The required vapor pressure equations are specified for the temperature calculation for the corresponding temperature range and the measuring gas used.

A specially designed gas pressure thermometer for determination of T_{90}, which likewise employs [3]helium or [4]helium according to the measuring range, is used from 3.0 K to 24.5561 K.

Platinum resistance thermometers are used as standard equipment in the temperature range from 13.8 K to 1234.93 K. The temperature is calculated from the ratio of the measured resistances $(R(T_{90}), R(T_{Tr}))$ at the temperature T_{90} and the temperature of the triple point of the water T_{Tr}.

$$W(T_{90}) = R(T_{90})/R(273.16) \qquad (2\text{-}13)$$

The use of the water triple point for definition of the resistance ratio $W(T_{90})$ is a noteworthy innovation compared to the definition of previous scales, which specified the reference temperature at the freezing point (273.15 K).

To enable explicit determination of the temperature, a reference function, which describes the temperature-dependence of the resistance ratio $W(T_{90})$ of an ideal platinum-resistance thermometer as reference thermometer, is defined for the temperature ranges 13.8033 K to 278.16 K and 273.15 K to 1234.93 K. The individual deviation function $W(T_{90}) - W_r(T_{90})$ must now be determined for each thermometer. The coefficients of the deviation functions are determined from the measured values of the resistance at the fixed points to be defined. The temperature values between the fixed points can then be determined with the aid of the deviation function and the reference function.

Platinum resistance thermometers, which are used in compliance with ITS-90, must meet extremely high measurement requirements. At present there is no platinum resistance thermometer, which meets these requirements over the full temperature range from 13 K to 1235 K.

The resistance thermometers currently used can be subdivided into the following three groups:

Encapsulated thermometers can easily be installed in cryostats because of their compact construction. In particular they are used to measure low temperatures. Their upper range of application extends to about 400°F. The resistance value at the triple point of water is 25 ohm.

Resistance thermometers equipped with quartz-glass or high-grade steel stems about 23 inches long are used from -310°F to 1000°F. The construction of the built-in measuring resistance is generally the same as in the encapsulated thermometer.

Specially developed thermometers are used for higher temperatures between 1000°F and 1763.2°F. The stems used consist exclusively of quartz glass. To achieve better stability of the measuring resistance at the high temperatures a thicker platinum wire is used. Consequently its resistance at the triple point of water is 0.25 ohm.

For temperatures above 1763.2°F (silver solidification point) the temperatures of the International Temperature Scale are measured by spectral pyrometers. The spectral radiation density $L_\lambda (\lambda, T_{90})$ of a so-called black body at the temperature T_{90} and the wavelength λ is related to the spectral radiation density $L_\lambda (\lambda, T_{reference})$ of a substance in thermodynamic equilibrium (e.g. silver solidification point) at the same wavelength and temperature of the selected fixed point. The temperature is defined by equation 2-14 in this range.

Virtually all temperature values differ from those in IPTS-68 as a result of the new definitions in ITS-90. Conversion functions and tables are made available for correction of existing deviations between the temperatures measured according to IPTS-68 and values according to ITS-90, so that the recalibration of practical thermometers can be avoided.

$$\frac{L_\lambda\,(T_{90})}{L_\lambda(T_{90}\,(\text{Reference}))}=\frac{\exp(c_2\,[\lambda\,T_{90}\,(\text{Reference})]^{-1})-1}{\exp\,(c_2\,[\lambda\,T_{90}]^{-1})-1}$$

(2-14)

L_λ = spectral radiation density of a black body with temperature T_{90}

λ = wavelength referred to the vacuum

c_2 = 2nd Planck's constant with the specified value c_2 = 0.014388 m · K

T_{90} = reference temperature, optionally silver (1234.93 K), gold (1337.33 K) or copper solidification point (1357.77 K)

The remaining **measuring uncertainties of ITS-90** are determined by the stability of the standard equipment and the reproducibility of the reference points established in the respective temperature range. The following values are specified as guide values:

Measuring uncertainties in the resistance thermometer

13.8 K	± 1 mK
933 K (1220°F)	± 5 mK
1235 K (1760°F)	± 10 mK

Measuring uncertainties in the spectral pyrometer:

1235 K	± 0.01 K
2500 K	± 2 K

The thermometers described thus far are used for determining the thermodynamic temperature according to the provisions of ITS-90. In the range from 13.8 K to about 903 K these thermometers can also be used for transmission of the defined temperatures as in the past. The vapor pressure and gas pressure thermometers as well as the resistance thermometers for high temperatures are less suitable for practical use. Therefore the temperature is transmitted with so-called **secondary thermometers** in the measuring range of this standard equipment.

These thermometers are calibrated by comparison with the specified standard equipment. For the range 0.65 K to 20 K the iron-rhodium resistance thermometer, or with smaller requirements on the measuring uncertainty, the germanium resistance thermometer is used for these purposes. The platinum-rhodium (10% rhodium)/platinum thermocouple is still used for the temperature range from 1168°F to 1947°F (631°C to 1064°C) with relatively large measuring uncertainties of 0.2 K to 0.5 K. However, it must be calibrated by comparison with the platinum resistance thermometer or partial radiation pyrometer. The newly developed gold/platinum thermocouple with a measuring uncertainty less than 0.1 K is also approved as a secondary thermometer for temperatures up to 1700°F (930°C) within this range.

Transmission of the temperature above 930 K is effected by calibrated tungsten-ribbon lamps and spectral thermometers.

Methods for approximation to the ITS-90 are described in the publications of the International Office for Weights and Measures [2.11, 2.12] from 1990.

2.2.4 Measuring principles and sensors for temperature measurement

2.2.4.1 Measuring principles on the basis of thermal expansion of substances

The volumetric expansion of gaseous, liquid or solid substances due to the effects of temperature is a fact of daily life. If the functional dependence of the thermal expansion of a substance is known from practical investigations or physical calculations and is reproducible, this substance property can be used for measurement of the temperature. The simplest possible linear relationships are of interest for the temperature measurement. However, such relationships can be found only in a limited temperature range because of the real behavior of the substances.

If the **linear expansion** of a bar as a function of a change in temperature is considered, the following formula generally applies:

$$dL = \alpha \cdot L \cdot d\vartheta \qquad (2\text{-}15)$$

The proportionality factor is a substance-related quantity and is designated the linear temperature coefficient. Its dimension is K^{-1}. If the length of this bar (L_0) at a specific reference temperature ϑ_0 is known, its length can be calculated for another temperature according to the following equation:

$$L_\vartheta = L_0 + L_0 \cdot \alpha \, (\vartheta - \vartheta_0) = L_0(1 + \alpha \cdot (\vartheta - \vartheta_0)) \qquad (2\text{-}16)$$

Simple thermometers, like the rod thermometer and bimetallic thermometer, which are based on this sensor principle, indicate temperature due to the different thermal expansion of two materials. They are described in Section 2.6.2.
The **thermal expansion behavior of a liquid** can basically be specified in a similar way. With β as cubic temperature coefficient

$$V_\vartheta = L_\vartheta = V_0(1 + \beta \cdot (\vartheta - \vartheta_0)) \qquad (2\text{-}17)$$

follows from equation (2-16)

The coefficient β is also quantity-dependent on the selected liquid, and can only be considered constant over a limited temperature range. Liquid glass thermometers use the thermal expansion of a thermometric liquid selected for a specific temperature range for direct indication of the temperature (Section 2.6.1). The liquid spring thermometers described in Section 2.6.2.3 also use the thermal expansion of a liquid as their operating principle. The field of application and the thermometer properties are essentially determined by the selected thermometric liquid for both types of thermometers.

The **vapor pressure of liquids** is a quantity heavily dependent on temperature, which makes it suitable for temperature measurement. However, the relationship between steam pressure and temperature is non-linear in this case. The vapor pressure is highly dependent on the temperature, in particular in the steep section of the vapor pressure curve (Figure 2.8.1 in Section 2.6.2.3).
With appropriate liquids, vapor pressure thermometers are used for accurate determination of very low temperatures. For example, vapor pressure thermometers are used to determine the thermodynamic temperatures in the range from 0.65 K to 3.2K.

The relationship between temperature, volume and pressure of a gas can easily be illustrated with the aid of the equation of state for an ideal gas.

$$p \cdot V_M = R \cdot T \qquad (2\text{-}18)$$

p	-	pressure
V_m	-	volume related to substance quantity
R	-	universal gas constant
T	-	temperature

The temperature can be measured according to this relationship in two different ways:

- measurement of the temperature-dependent volume difference at constant pressure
- measurement of the temperature-dependent pressure difference at constant volume.

Both methods are used to accurately determine the temperatures of the International Temperature Scale ITS-90 with the aid of gas thermometers at the specified fixed points.
Industrial gas pressure spring thermometers operating on the basis of the equation of state for real gases are dealt with in Section 2.6.2.3.

2.2.4.2 Electrical temperature sensors

Electrical temperature sensors convert the physical quantity "temperature" into an electrical signal dependent on it. Electrical thermometers are self-contained components, which supply a processible signal as their output. Depending on the sensor principle an external power supply is usually required.

An important advantage results from the good transmissibility of these electrical signals over long distances. Therefore the temperature measuring and indication points may be far apart. The measuring signals can be installed and processed at low cost in control and regulating systems or process control systems.

Resistance thermometers and thermocouples today play an important part in industrial thermometry.

Metal resistance thermometers

Metal resistance thermometers are equipped with sensor elements on the basis of metallic conductors, which change their electrical resistance as a function of the temperature.

This change in resistance can be measured with the aid of an electrical measuring circuit consisting of the sensor element, an auxiliary voltage source and a measuring instrument.
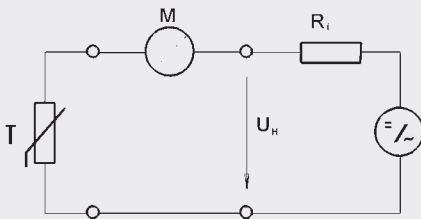
Figure 2.4 Basic measuring circuit for resistance temperature sensors

The current flowing in the measuring circuit is a function of the temperature being measured. This basic design of measuring circuit can also be used for other non-metallic resistance temperature sensors, i.e. semiconductor sensors. Since these temperature sensors are based on a different physical principle, they are dealt with separately.

The change in the electrical resistance of pure metals as a function of temperature is a basic physical effect, the cause of which can be found in the conduction mechanism of the metals themselves. The basis of the conductivity of metals is the freely mobile electrons in the atomic lattice. Their number and kinetic energy are temperature-dependent. The natural vibration of the lattice atoms of the metal impede the movement of the electrons. If energy is supplied to the metal atoms via a temperature increase, they vibrate with a proportionally larger amplitude and frequency. A mechanical resistance reduces the mobility of the electrons and there is a proportional increase in the electrical resistance. As the electrical resistance increases with temperature in this case, these materials are said to have a positive temperature coefficient.

The physical relationship between the temperature of a metallic conductor and its electrical resistance is not linear and can be accurately described only by a polynomial of a higher order. Depending on the requirements of the respective temperature measurement it may be possible to neglect the quadratic and higher order terms. With $\Delta t = t - t_0$ the following applies:

$$R(t) = R_0 \left(1 + a \times \Delta t + b \times \Delta t^2 + c \times \Delta t^3 + \ldots\right)$$
$$(2\text{-}19)$$

R_0 is the resistance value of the electrical sensor at a reference temperature (e.g. $t_0 = 0°C$). The material-related temperature coefficients are designated a, b and c in this case. They can be regarded as constant only in a limited temperature range. Therefore the specification of their values

must always be referred to a defined temperature range (i.e. 32°F to 212°F [0°C to 100°C]).

Metallic materials which are to be used for temperature measurement, must meet the following basic requirements:

- good reproducibility of the change in electrical resistance as a function of temperature
- high temperature coefficient
- low specific resistance
- small dependence on other physical quantities, i.e. pressure
- resistance to corrosion and chemical impurities
- high long-term stability.

A number of materials such as copper (Cu), nickel (Ni), molybdenum (Mo), platinum (Pt) and others are suitable for temperature measurement. However, nickel and in particular platinum have been adopted as preferred materials for temperature measuring resistors in industrial applications because of their desirable properties.

Platinum measuring resistors are used in the temperature range between -330°F and 1560°F (-200°C and 850°C), and nickel measuring resistors in the range from -76°F to 482°F (-60°C to 250°C).

The construction of important types of platinum measuring resistors and their use in electrical resistance thermometers are described in Section 2.7.1.

Thermocouples

The thermocouple is a temperature sensor which supplies an electrical voltage directly dependent on the temperature without an additional power source because of its thermo-electric properties. Two different metallic conductors are connected to each other at their ends. If the junctions are at different temperatures, a DC voltage can be measured by interposition of a measuring instrument in the thermal circuit formed in this way. It is a measure of the temperature difference between the two junctions. If one of the temperatures is known and the other is constant at the time of

measurement, the voltage can be used for measurement of the temperature.

The phenomenon of **thermoelectricity** described by Seebeck in 1821 belongs together with the Peltier and Thomson effect to the group of thermoelectric effects. They can be described on the basis of Boltzmann's transport equation. The thermoelectric effect is a complex physical process, which according to recent findings is based on the temperature-dependence of electron potentials in electrical conductors. According to these findings an electrical field from the hot to the cold end already occurs in an individual conductor located in a thermal field with temperature gradients. Integrated over the length of the conductor this electrical field causes a potential difference U.

$$E = S\, degreeT; \quad \Delta U = -Edx$$

$$U = \int_{T_1}^{T_2} SdT \qquad (2\text{-}20)$$

E = electrical field
S = thermoelectric power
U = voltage

This charge transfer can be viewed as a direct effect of the conservation of momentum of the electrons in the metal lattice via the conductor volume. Many charge carriers with lower energy at the cold conductor end compensate for the pulses of fewer carriers heated up far more quickly at the end heated by an energy source. This is shown schematically in Figure 2.5. For the sake of simplicity the positive charge carrier (metal ions) is not shown. The electron distribution of a conductor in the homogeneous temperature field is shown under a) in Figure 2.5 for comparison. Therefore a substantially larger number of electrons, though with lower energy, are present at the cold end of the conductors heated at one

end (Figure 2.5 b). This voltage difference cannot be satisfactorily measured in practice, because further conductors must always be connected to the hot or cold end for measurement, and their thermal EMF's considerably distort the measurement result.
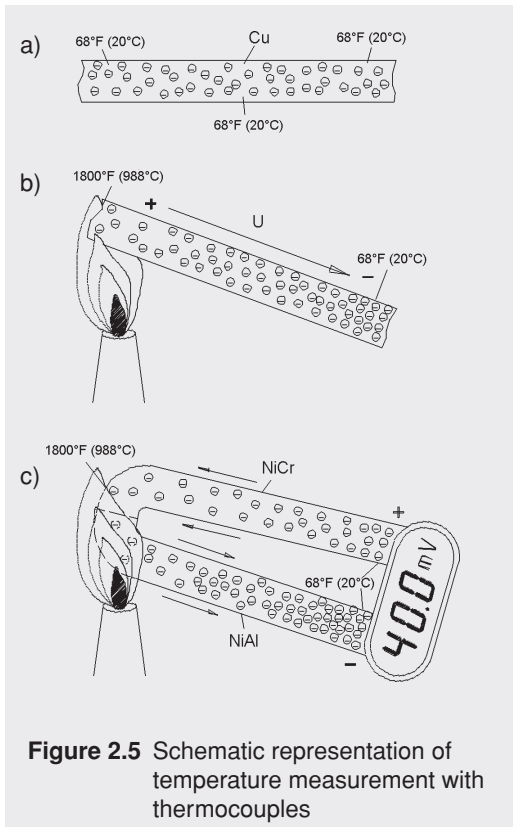
Figure 2.5 Schematic representation of temperature measurement with thermocouples

If a thermocouple consisting of two suitable materials, i.e. NiCr and NiAl which are connected at the measuring point, is used, a thermal EMF of this material pairing can be measured (Figure 2.5 c). The electrons in the NiAl wire can move about four times more easily than in the NiCr. Therefore the cold end of this wire is overcharged with electrons to a greater extent than the cold end of the NiCr wire. A potential difference exists between the two wire ends. The electron excess at the cold

NiAl wire end penetrates into the cold end of the NiCr wire via the measuring instrument. The electrons present there are transported into the hot section of the NiCr wire despite the collisions of the faster electrons. They again acquire a higher velocity as a result of the energy supply in the flame and return to the hot section of the NiAl wire. The circuit is closed from this point and the corresponding portion of the electrons again returns to the cold end of the NiAl wire as a result of the conservation of momentum with energy loss. In the example specified a current of 4 mA flows when the temperature difference between hot and cold wire ends is 968°C and the resistance of the entire circuit is 10 ohm (including internal resistance of the measuring instrument). The voltmeter indicates the specified voltage difference of 40 mV.

The difference between the absolute thermal EMF's of the material pairing A and B is generally obtained as a measurable quantity.

$$U = \int_{T_1}^{T_2} (S_A - S_B)\, dT \qquad (2\text{-}21)$$

If both wires are viewed as elementary batteries, their difference is indicated at the measuring instrument. It is dependent only on the temperature gradient and the specific material properties of the thermal wires. As the thermal EMF's of the individual thermal wires vary with the temperature according to the material, the measured voltage exhibits the typical curve for the selected thermocouple.

When both conductor ends of the thermal wires are connected, a thermal circuit, in which a current flows according to the voltage difference and the internal resistance, results (Figure 2.6).

Some important fundamental laws relating to measurement, which can be understood on the basis of the physical theory presented in simplified form above, are now dealt with for thermocouples.

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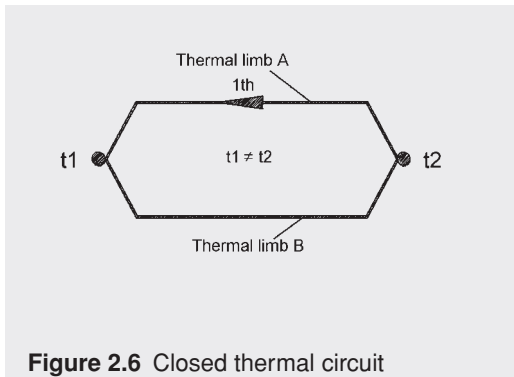
Figure 2.6 Closed thermal circuit

The law of **linear superposition** applies to thermocouples. According to this law a thermocouple can be viewed as broken into a number of individual thermocouples (Figure 2.7)
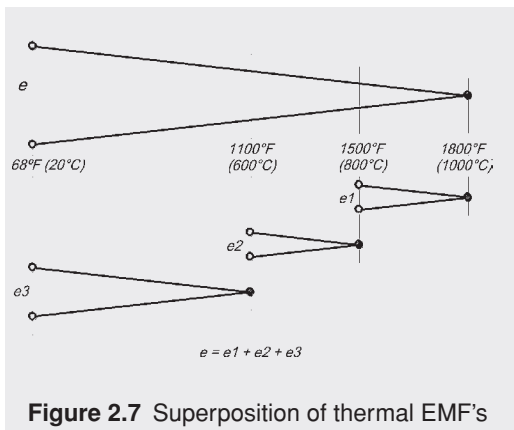
Figure 2.7 Superposition of thermal EMF's

If the respective measuring point and reference point temperatures are taken into account, the measurable total voltage of the thermocouple is equal to the sum of the voltage of the individual thermocouples. Taking into account this law it is clear that an additional hot area between the measuring point and reference point cannot affect the resulting thermoelectric voltage because the elementary battery voltages from the normal area to this area and vice versa offset each other.

According to the law of **homogeneous temperature** the sum of all thermoelectric voltages in a thermal circuit with an optimum number of material combinations is equal to zero, if all parts of the circuit are at the same temperature. In practical applications this means that non-homogeneous transition areas, other line materials and material combinations in plug areas do not affect the thermoelectric voltage, if reasonable measures are taken to ensure that no temperature gradient occurs between the transition points.

According to the law of the **homogeneous circuit** the temperature of the homogeneous conductor between measuring and reference point has no effect. Mechanical or thermal changes or non-homogeneous areas of the wires do not affect the thermoelectric voltage as long as they are in a homogeneous temperature field.

Many **material combinations** are suitable for thermocouples. A prerequisite is a sufficiently large, preferably linear and readily reproducible dependence of the thermal EMF on the temperature. In addition these materials must meet other requirements such as:

- highest possible melting point,
- high resistance to reducing or oxidizing media,
- small foreign alloy formation,
- small cold brittling at low temperatures,
- good deformability and processibility (soldering, welding).

Over 300 material combinations (thermocouples) are currently known for temperature measurement. The thermoelectric voltages of industrially used material combinations are usually 5 mV/K to about 100 mV/K.

Materials suitable for temperature measurement can be shown arranged according to thermoelectric voltages in a thermoelectric series usually in relation to platinum as reference metal (Figure 2.8).

The temperature range for thermocouples is between -420°F and 4300°F (-250°C and 2400°C) depending on the type.

The most common industrial thermocouples are described in Section 2.7.2.

Tellurium	50
Silicone	45
Silit	27
Antimony	4 8
Nickel-chromium (85 Ni, 10 Cr)	2.55
Iron	1.9
Platinum-rhenium	1.5
Molybdenum, uranium	1.2
Brass	1.1
Indium-rhodium (40 Ir, 60 Rh)	1.0
Tungsten, high-grade steel (V2A)	0.8
Copper	0.75
Silver, gold, zinc	0.7
Manganin (86 Cu, 12 Mn, 2 Ni)	0.68
Rhodium	0.65
Indium-rhodium (40 Ir, 66 Rh)	0.64
Platinum-rhodium (10%)	0.64
Iridium	0.63
Phosphor-bronze	0.52
Tantalum, cesium	0.5
Lead, iridium-ruthenium	0.45
Aluminum, magnesium, tin	0.4
Graphite	0.2
Platinum, mercury	0.0
Thorium	-0.1
Sodium	-0.21
Palladium	-0.3
Potassium	-0.94
Nickel silver (Cu, Ni, Zn)	-1.0
Nickel	-1.55
Cobalt	-1.6
Constantan (55 Cu, 45 Ni)	-3.5
Bismuth, at right angles to the axis	-5.2
Bismuth, parallel with the axis	-7.7 in mV

PtRh-Pt

NiCr–Ni: 2,55 – (-1,55) = 4,1 mV

Figure 2.8 Thermoelectric series in relation to platinum at 212°F (100°C) measuring point temperature and 32°F (0°C) reference point temperature

Semiconductor sensors

Resistance thermometers with semiconductor measuring resistors use the temperature-dependent change in the electrical resistance of semiconductive, usually ceramic, materials for temperature measurement. They are ideal in the temperature range from -150°F to +752°F (-100°C to + 400°C). **Cold conductors** (PTC resistors, positive temperature coefficient), **hot conductors** (thermistors, NTC resistors, negative temperature coefficient), **silicon-based measuring re-**

sistors (spreading resistance), semiconductor diodes and **integrated temperature sensors** are fundamentally different and are dealt with separately in this section.

Semiconductor resistance thermometers are used, for example, in portable measuring equipment for measurement in small temperature ranges or as temperature sensors in anemometers and psychrometers. Thermistors are commonly used in the plastics and food industries because of their ruggedness and fast response.

A **cold conductor** is a temperature-dependent semiconductor resistor, the resistance value of which rises suddenly when a specific reference temperature is achieved. As a result of the extremely high positive temperature coefficients in this range, which may typically be between 7%/°C and 70%/°C, cold conductors are also designated PTC resistors. The transition temperature and the maximum operating voltage are specified in the data sheets of the manufacturers for a specific reference temperature (77°F to 400°F [25°C to 180°C]).

Cold conductors are made of doped polycrystalline ceramic material based on barium titanate ($BaTiO_3$), which is known to be a good insulator. The semiconduction is created by selective doping with substances with a higher chemical valency than the lattice modules of the ceramic material. The cause of the typical cold conductor effect lies in the fact that the material structure consists of many small crystallites (Figure 2.9).

135
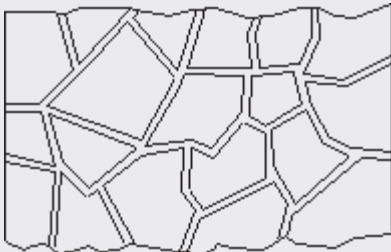
$$R_{KL} = R_{grain} + R_{grain\ boundary\ layer}$$
$$R_{grain\ boundary\ layer} = f(T)$$

Figure 2.9 Schematic diagram of the poly-crystalline structure of cold conductor ceramic material

R_{min}	=	minimum resistance (resistance value at TR_{min})
TR_{min}	=	temperature at R_{min} (start of positive aR)
R_b	=	reference resistance (resistance value at T_b)
T_b	=	reference temperature (start of steep increase in resistance)
R_p	=	resistance in the steep range (resistance value at T_p)
T_p	=	temperature above the reference temperature T_b

Figure 2.10 Typical resistance/temperature characteristic curve of a cold conductor

The total resistance of the cold conductor is composed of the resistance of the individual crystallites and that of the grain boundary layers. The latter is dependent to a large extent on the temperature. Figure 2.10 shows a typical resistance/temperature characteristic curve.

R_N = cold conductor average resistance (resistance value at TN)

Because of the frequency-dependence of the PCT effect the electrical data for the cold conductor applies only at low frequencies.

Cold conductors are predominantly made as disc-shaped elements with diameters between 5 and 10 mm. Because of their characteristic curve they are particularly useful as limit temperature switches in machines and plants.

Hot conductors are often also called thermistors or NTC resistors. They are temperature-dependent semiconductor resistors, the resistance values of which diminish as the temperature rises. The negative temperature coefficients vary between about -2%/°C and -5%/°C.

Hot conductors consist of polycrystalline mixed oxide ceramic materials such as Fe3O4, Zn2TiO4 or MgCr2O4 with NiO, CoO and Li2O additives, which are manufactured at high temperatures in a sintering process.

The conduction mechanism of cold conductors is extremely complex. Extrinsic conduction, intrinsic conduction or valency conduction may occur. Their electrical behavior is essentially determined by the material properties and the sensor type selected.

Examples of typical designs are as follows:
disc-shaped NTC 3 mm x ø5.5 mm dia.
rod-shaped NTC 7 mm x ø1.6 mm dia.
miniature NTC   ø0.2 to ø1 mm dia

Hot conductors are used in temperatures roughly
ranging from −160°F to 600°F (-110°C to 300°C).
However, temperatures up to 1100°F (600°C) can
be measured by special high-temperature types.
Resistance values at the reference temperature
(average resistance value) of 3 Ω to 1 MΩ with
limit value deviations of 20% or 10% are techno-
logically feasible. The limit value deviation of the
nominal resistances of hot conductors can be re-
stricted to less than 3% by sorting processes and
subsequent sintering.
The resistance of hot conductors is approximately
exponentially dependent on the temperature. It is
specified by characteristic curves in the data
sheets of the manufacturers.

The relationship

$$R_r = R_{T_0} \cdot \exp B \left(\frac{1}{T} - \frac{1}{T_0} \right) \qquad (2\text{-}22)$$

T	= temperature in K
RT	= resistance at temperature (T)
RT_0	= resistance at the reference temperature
T_0	= reference temperature in K
B	= constant in K dependent on the shape and material

roughly applies to the characteristic curve.

The R_{T_0} and B values are subject to fluctuations
during production. B is dependent on the tempera-
ture. It is determined in a limited area by measure-
ment of the resistance values (R_1, R_2) of the NTC
resistor at defined temperatures (T_1, T_2). B is then
calculated from the following relationship:

$$B = \frac{\ln \dfrac{R_1}{R_2}}{\dfrac{1}{T_1} - \dfrac{1}{T_2}} \qquad (2\text{-}23)$$

The values specified for B in the data sheets are
generally determined from the resistance values
at 77°F and 185°F (25°C and 85°C). They are
between 1500 K and 7000 K. A resistance tem-
perature characteristic curve is shown in Figure
2.11 with B as parameter.
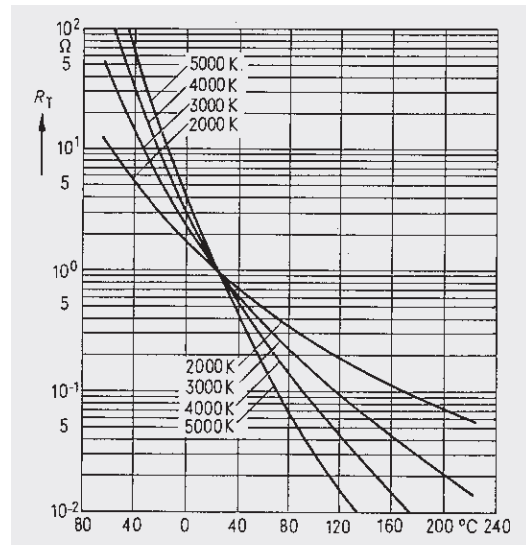
Figure 2.11   Resistance temperature
characteristic curves of NTC
resistors with B as parameter

The current flow through a hot conductor causes
self-heating, which leads to an additional tempera-
ture error of the sensor. In addition the maximum
permissible electrical load must not be exceeded.
The following relationship applies to the power
loss:

$$P_V = I_M^2 \cdot R_T \qquad (2\text{-}24)$$

P_V	= power loss of the thermistor
I_m	= measuring current
R_T	= resistance at temperature T.

The excess temperature Δt_e can be calculated directly from this relationship:

$$dT_e = \frac{I_M^2 \cdot R_T}{G_{TH}} \qquad (2\text{-}25)$$

Δt_e = excess temperature
G_{th} = thermal conductance of the hot conductor

The thermal conductance of the hot conductor is specified in the data sheet of the manufacturer. The user must try for the smallest possible power loss during operation of the hot conductor, because even small power losses cause temperature errors due to self-heating. To allow connection of different sensors to the same measuring instrument, the NTC resistors are adapted to the specified characteristic curve. This is accomplished via resistance networks with a stable temperature, the values of which are calculated with the aid of measured resistance values of the hot conductor at three different temperatures.
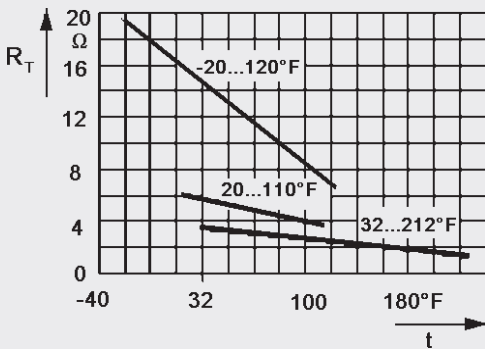
Figure 2.12 Linearized resistance characteristic curves of special thermistors

In some modern thermometers the indicator is equipped with an integrated amplifier and sensor with standardized characteristic curves. This makes it possible to have limit value deviations of 0.05% of the respective resistance value from

–112° to 570°F (-80°C to 300°C). Some manufacturers offer thermolinear thermistors in various basic value series from –22°F to 212°F (-30°C to 100°C) [Figure 2.12].
If these thermistors are operated from –23°F to 113°F (-5°C to 45°C), adjustment errors of ± 0.27°F (0.15°C) and linearity deviations of 0.11°F (0.06°C) can be achieved. A simple linear equation can then describe the dependence of the resistance on the temperature for sensors of this type.

$$R = a \cdot t + b \qquad (2\text{-}26)$$

t = temperature in °F
a, b = type-related constants

Silicon measuring resistors (spreading resistance sensor) have a positive temperature coefficient. From –95°F to 320°F (-70°C and 160°C) their resistance varies, for example, from 14 W to 4 kW. A feature of the characteristic curve of Silicon measuring resistors is its small non-linearity, which can be linearized very easily by a series resistor (with voltage feed) or by a parallel resistor (with current feed) (Figure 2.13).
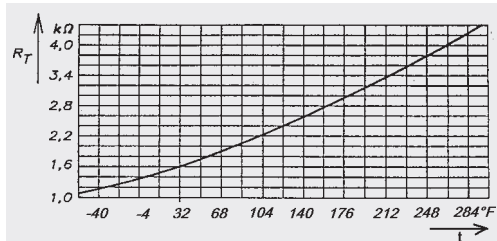
Figure 2.13 Characteristic curve of a spreading resistance sensor

Linearity deviations of less than ±1.8°F (1°C) between -58°F to 300°F (-50°C to 150°C) or better than ±0.36°F (0.2°C) in the restricted range from 32°F to 212°F (0°C to 100°C) can be attained. Si measuring resistors are available with a limit value deviation of 1%. They are characterized in particular by high long-term stability and relatively high temperature coefficients.

Semiconductor diodes and integrated temperature sensors are a group of semiconductor sensors which should not go unnoticed.

If a suitable semiconductor diode (pn junction), for example, is operated in the forward direction and supplied with a constant current, the conducting voltage is a function of the temperature. In a limited temperature range (-58°F to 300°F [-50°C to +150°C]) this relationship is virtually linear. The following applies to Silicon as the basic material:

$$U_D(T) = C \cdot T \qquad (2\text{-}27)$$

U_D = conducting voltage
C = constant with approx. -2 mV/K
T = temperature in K

Germanium, Silicon and above all Ga-As diodes are used in the low temperature range from 1 K to 400 K.

When high linearity is required, the use of transistors is still more practical because linearization is possible in this case by external adjustment of the temperature response of the outer barrier layer to ±1%.

In **integrated temperature sensors** the required constant current source, for example, is also integrated on the chip. Other integrated temperature sensors already supply a measuring signal of the same frequency at their output.

Radiation thermometers (pyrometers)

Pyrometers are used for indirect (non-contact) temperature measurements. A brief description is limited to the basic principle and the most important basic types of pyrometer. Further information on this subject can be obtained directly from their manufacturers.

Pyrometers are used at standard measuring temperatures from −150°F to 6300°F (-100°C to 3500°C) and up to 9000°F (5000°C) in special cases.

Pyrometers can be used, if:
- the surface temperature is to be determined,
- the medium to be measured is visually accessi-

ble (window, openings, optical fiber).

In the following cases it is either better to use pyrometers than contacting thermometers, or (in some cases) it is only possible to use pyrometers:
- at high temperatures (> 2500°F / 1400°C),
- with moving objects,
- with small objects (wires, filaments, ...),
- with objects with low heat capacity or small thermal conductivity (foam, soap bubbles, glasses,...)
- with rapid temperature changes in the milli- or microsecond range,
- with simultaneous recording of variable temperature distributions or temperature fields.

Basic principle: the thermal radiation (infrared to visible range) of a measured object is filtered optically and concentrated on a radiation receiver. Its electrical reaction consists of a change in the resistance, voltage or current of the radiation receiver induced directly or indirectly via a temperature increase depending on the principle used. The electrical change is amplified, measured and processed further.
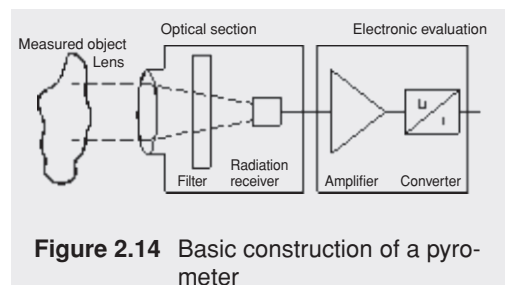
Figure 2.14 Basic construction of a pyrometer

Basic types of pyrometer

Total radiation pyrometer

Measurement and summation of the full thermal radiation spectrum (wavelengths from 0.5 µm to 40 µm). **Thermal radiation receivers (bolometers, thermocouples, pyroelectric detectors)**, which have a uniform sensitivity over the full spectrum, are used as radiation receivers. Total radiation pyrometers supply an output signal, which roughly conforms to the Stefan-Boltzmann radiation law.

Spectral pyrometer

Only a narrow spectral range can be measured using optical filters and selective receivers. Therefore in addition to the thermal radiation receivers **photoelectric radiation receivers** (e.g. **photocells, photomultipliers, photoresistors, photodiodes, photodetectors**), which have a selective spectral sensitivity, can also be used. If the measured object is a "classic" **black or gray radiator**, the output signal roughly conforms to the Stefan-Boltzmann radiation law.

Ratio pyrometer

A variation of the spectral pyrometer. The radiation density of the measured object is determined for two different, closely spaced wavelengths λ_1 and λ_2. The measured object temperature can be determined via Wien's law from the ratio of the two spectral densities.

Bandpass pyrometer

A wide spectral range is selected optically and measured. Depending on the type of construction and bandwidth, the bandpass pyrometer can be regarded as a spectral pyrometer with **effective wavelength** λ_e with small temperature differences.

Disappearing-filament pyrometer

The disappearing-filament pyrometer is a special type of bandpass pyrometer. The surface color of a hot body (> 1200°F / 650°C) is compared visually with the glowing color of a tungsten filament by the human eye. The objects measured temperature is determined by matching the heating current to the optical color of the filament.

Thermographic equipment

Thermographic equipment measures the temperature distribution over the area of the measured object (x-y distribution). It consists of a high-speed, optically focusing pyrometer (detector), which scans the measured object opto-mechanically point by point (**scanning radiation thermometer**) or a whole line of miniaturized pyrometers (**line scanner**), which scan the surface of the measured object line by line. **Peltier-cooled detectors** are generally used as radiation receivers.

2.2.4.3 Additional temperature measuring techniques

Optical measuring methods

Radiation thermometers can also be used for optical measuring techniques. Using optical measuring techniques the intensity or wavelength of the electromagnetic radiation emitted by a body according to its temperature is measured (Section 2.2.4.2). In contrast the temperature measuring techniques of interest in this section use an "optically active body" as the sensor. Basically, a distinction can be made between two groups. One group consists of measuring methods which use the temperature-dependent light reflection or absorption properties of substances for temperature indication (heat sensitive colors, liquid crystals). The second group contains measuring techniques, which use real optical sensors as part of a measuring chain (sometimes combined with electrical sensors) for temperature measurement.

Heat sensitive colors use physical effects of substances, which change their optical properties as a function of temperature. They are applied in the form of dyes, liquids or chalk on the surface being measured. The color of these temperature indicators changes suddenly when a specific critical temperature is reached. Depending on the selected substance mixture, several critical temperature points (up to 4) can be measured to show the temperature distributions on surfaces. A distinction is made between reversible dyes, the color of which changes back to the original color after the temperature falls below the critical point, and irreversible dyes. The dyes for heat sensitive colors are manufactured in graduations of 50°F to 200°F (10°C to 100°C) for the temperatures ranging from 100°F to 2500°F (40°C to 1350°C). The measuring uncertainty is 5%, because the critical point depends on the exposure time and rate of temperature increase.

Heat sensitive colors are also offered in the form of self-adhesive strips with dots or lines. Several heat sensitive colors are often put on a strip. The corresponding temperatures are printed alongside (Figure 2.15).

a) Measuring strip   b) Measuring dot

°F
□ 110
□ 104
■ 99
■ 88
■ 82
■ 77
■ 71

Temp. reached 99° F   Temp. reached 46°F
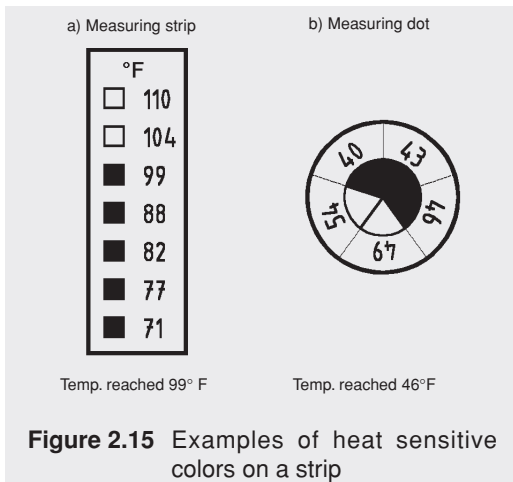
Figure 2.15 Examples of heat sensitive colors on a strip

Liquid crystals can also be used to indicate surface temperatures and to visually display temperature fields. Specific liquid substances are used (e.g. cholesterol), which as thin layers like crystals have anisotropic properties. The molecule axes of superimposed layers of these liquids are each turned by a small angle in relation to each other, so that a helical structure results. With exposure to polarized light these layers are bi-refractive. This means that according to the direction of rotation of the helix the light is broken down into a clockwise-polarized reflected and counterclockwise-polarized transmitted portion. The wavelength of the reflected light λ_R is proportional to the pitch P, which is in turn dependent on the temperature (Figure 2.16).

a) Layer structure   b) Light reflection   c) Reflection factor
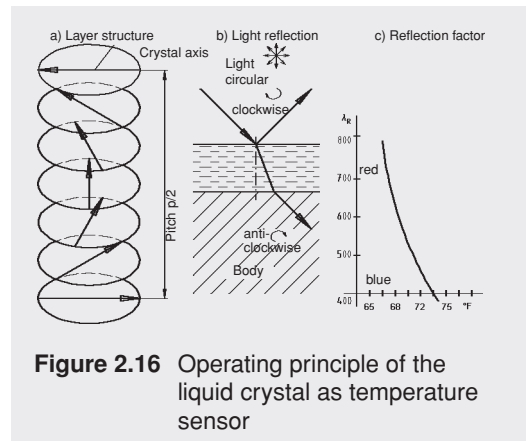
Figure 2.16 Operating principle of the liquid crystal as temperature sensor

In measurements on surfaces with white light present, different wavelengths, which can be evaluated as different measuring colors by the observer, are reflected proportional to the temperature distribution on the surface.

The temperature sensitivity of LCD temperature indications can be adjusted by varying the selection of substance mixtures. With temperature ranges from 32°F to 176°F (0°C to 80°C) temperature intervals of 1.8°F to 18°F (1°C to 10°C) are possible for a color change in the full visible spectral range.

Fiber-optic thermometers belong to the second group of the optical measuring methods mentioned above. Starting from a coherent light source (laser) the light passes through two glass fibers, a measuring fiber and a reference fiber. In a receiver the light from the two fibers is brought to interference and evaluated. This temperature measuring method is not very useful for practical applications. The so-called **luminescence thermometers** use a sensor element equipped with a luminescent substance at the end of a glass fiber. Two possible techniques are used for temperature measurement.

a) Measurement of the temperature-dependent wavelength displacement of the luminescent light.

b) Measurement of the temperature-dependent time constant, with which the luminescent light decays after pulse excitation.

Various substances are used as sensor materials such as zinc sulphide, or preferably aluminium-doped gallium arsenide crystals or YAG laser crystals. Temperatures up to 750°F (400°C) are measurable with this method. The independence of these optical measuring methods from electro-magnetic fields should be emphasized. They are suitable for use in areas with an explosion hazard and in processes with high electrical potentials.

Crystal oscillator temperature sensors

It is well known that crystal oscillators are used as a reference in pulse generators for computers, quartz clocks and other digital technology.
The consistency and small temperature depen-dence of the resonance frequency of the crystals is important in this respect. However, this property applies only to a specific cut direction of the crys-tal with regard to its optical axes. Since the elas-tic properties of a quartz crystal and its tempera-ture sensitivity are dependent on the crystal direc-tion, it is possible to find cutting angles at which sufficiently high temperature coefficients of the resonance frequency of the quartz suitable for temperature measurement are reached.
For example, a quartz sensor cut at a specific angle has an almost linear temperature-depen-dence of 35 ppm/K between –110°F and 500°F (-80°C to 250°C).
Quartz thermometers have been used in labora-tories for more than 30 years. The basic principle of such thermometers is shown in Figure 2.17.

The frequency of an oscillator measured by a measuring crystal is combined with the reference frequency of an oscillator not dependent on tem-perature. The differential frequency produced at the output is proportional to the measured tem-perature and can be measured with a counter and indicated during a defined measuring period.
The measuring range of conventional quartz digi-tal thermometers is between –110°F and 600°F (-80°C and 300°C). In the limited temperature range from –15°F to 230°F (-10°C to 110°C) measuring uncertainties in the mK range can be reached, if these thermometers are adequately calibrated.

In 1986 a new type of crystal oscillator thermo-meter was introduced, in which the temperature-sensitive crystal oscillator is housed in a standard measuring element. The oscillator is fitted with a special electronic processor in the connection head. The crystal oscillator used has a cutting angle which has a temperature coefficient of al-most 100 ppm/K of the resonance frequency. It is noteworthy that the temperature coefficient of this Y cut depends only slightly on the cutting angle tolerances in production. Such crystal oscillator temperature sensors can be manufactured in ex-isting plants for "normal" AT crystals, which are produced by the millions.
The frequency/temperature characteristic of this crystal oscillator is not linear, but well reproducible. It can be described approximately with a polyno-mial of the 5th order (equation 2-28).

Figure 2.17   Principle of the quartz
thermometer
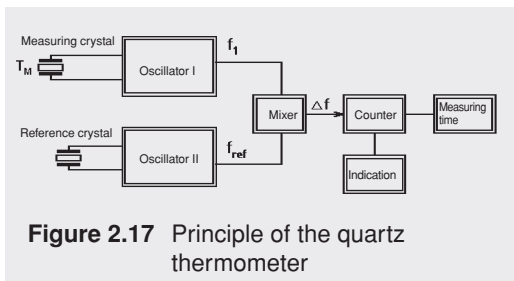
$$f\,(T) = F_0 \cdot \left[\, 1 + \sum_{i=1}^{i=5} a_i \cdot (T - T_0)^i \,\right] \qquad (2\text{-}28)$$

T_0 = reference temperature
F_0 = frequency at the reference temperature T_0
a_i = temperature coefficient dependent
on the crystal

Manufacturing deviations in the resonance frequency at the reference temperature are easily compensated by digital single-point calibration in the sensor electronics (Figure 2.18).
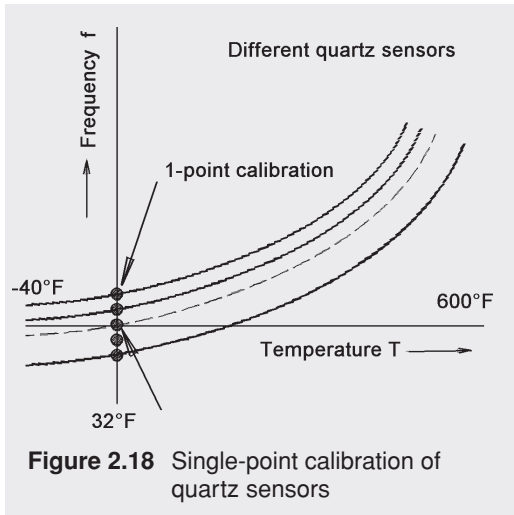
Figure 2.18 Single-point calibration of quartz sensors

After artificial pre-aging these thermometers achieve long-term stability's of 1 to 3 ppm/year between –110°F and 600°F (-80°C and 300°C). Quartz sensors cannot be used above 1060°F (573°C) because the crystal loses its piezoelectric properties at higher temperatures.
In the temperature range from –4° to 265°F (-20°C to 130°C) system accuracies (sensor, transmission line and evaluation system) of ± 0.18°F (0.1°C) and in the full temperature range a maximum measuring error of ± 0.54°F (0.3°C) are specified.
The small quartz sensors with diameters of 0.18 inch (4.5 mm) and smaller allow for assembly in conventional measuring elements.
The sensor electronics digitize the oscillator frequency and supply a pulse interval modulated signal at the output, i.e. the measured temperature information is now contained in the interval between two pulses (Figure 2.19).
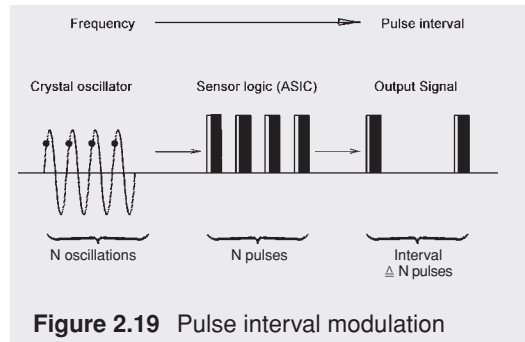
Figure 2.19 Pulse interval modulation

These output signals can be transmitted over long distances with a high signal-to-noise ratio and processed further in an evaluator virtually "without" loss of accuracy.
Quartz thermometers with pulse interval modulated output signals have a bus capability.

Acoustic measuring methods

Acoustic temperature measuring methods use the temperature dependence of the velocity of sound in various substances for temperature measurement. A distinction is made between **resonant measuring methods** and **non-resonant methods**, in which sound propagation time measurements, for example, are seen.

The output signal is a frequency or time interval, which can easily be digitized. The measuring sensors of **non-resonant solid-state sensors** consist of a 2 inch long (50 mm) rhenium wire with a diameter of 0.02 inch (0.5 mm). These sensors operate on a pulse echo principle. They are particularly used to measure extremely high temperatures up to about 5500°F (3000°C). Measuring uncertainties of about 1% can be expected with them.
Acoustic gas thermometers use the temperature-dependent sound velocity in gases for temperature measurement. Any gas can be used as the sensor material. The sound velocity in gases can generally be described as a function of temperature by the following relationship:

$$c(T) = c_0 \cdot \sqrt{\frac{T}{T_0}} \qquad \text{(2-29)}$$

T = absolute temperature in K

T_0 = optional reference temperature

c_0 = sound velocity at reference temperature (T_0)

Acoustic temperature measuring methods are predominantly non-contact. The average temperature taken over the measuring distance, the length of which must be known, is given as the measurement result.

Handy immersion sensors, in which a measuring gas is contained in a thin tube, are further developments of the gas thermometer principle. These thermometers operate according to a modified pulse echo method. Various gases including air can be used as the measuring gas. The immersion tube is made of ceramic, glass, metal or other material. Temperatures up to the load limit of the selected tube material can be measured with these thermometers. The specified temperature resolution is less than 0.1K, with measuring uncertainties of less than 1K.

Temperature indicators

The **Seger cone** is a well-known temperature indicator. It is used primarily in the ceramic industry. Seger cones in graduations of 20°F to 120°F (10°C to 50°C) are available for temperature ranges between 1100°F and 3600°F (600°C and 2000°C).

The cones with heights of 0.1 in. to 0.25 in. (2.5 cm to 6 cm) are made of ceramic blocks with various compositions. When heated they soften and bend over. The "Seger drop point" specified on the cones corresponds to the temperature at which the apex of the cone touches the supporting surface. This temperature depends on the heating time.

Because of their composition Seger cones behave like glazes and ceramic blocks. They can be used to supply information on the so-called "finishing firing temperature".

So-called **temperature characteristic bodies**, which indicate a specific temperature by melting or softening, are also used in the ceramic industry. Their geometrical shape changes significantly as a result of gravitation or the surface tensions occurring at the corresponding temperature. Organic compounds with an accurate melting point are used for lower temperatures. Metals and metal alloys are used in higher temperature ranges. These generally cylindrical bodies are offered in temperature ranges from 212°F to 2900°F (100°C to 1600°C) with melting points at intervals of 35°F (20°C). They often do not have an accurately defined melting point, so that they melt down only in a specific temperature interval. In addition, this process is time-dependent. However, these bodies melt within no more than 10 minutes at the specified rated temperatures. The uncertainties are specified as ± 4°F (7°C).

Thermal noise thermometers

Thermal noise thermometers are highly accurate temperature measuring instruments, which are useful for measuring thermodynamic temperatures. Measuring uncertainties of 0.1% can be expected for temperatures from 300 K to 1200 K. The thermometer principle is based on the temperature-dependence of the mean velocity of the electrons in a resistor not under load (Brownian movement).

Nyquist derived the theorem named after him for this temperature measuring method from general thermodynamic considerations.

$$\overline{u^2} = 4 \cdot k \cdot T \cdot R \cdot \Delta f \qquad \text{(2-30)}$$

$\overline{u^2}$ = mean noise voltage square in the frequency band between f + Df

R = electrical resistance independent of the frequency in this frequency band

T = thermodynamic temperature

k = Bolzmann constant, $k = 1.38066 \; 10^{-23}$ J s

The values of the resistance R and the frequency range, in which measurements are carried out, are parameters.

The basic circuit of a thermal noise thermometer shown in Figure 2.20 can be derived from the specified equation (2-30).
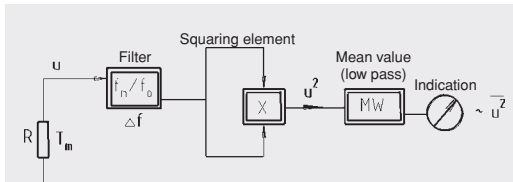
Figure 2.20 Basic circuit of a thermal noise thermometer

Difficulties occur in practical measurements because the thermal noise of amplifier modules, supply leads and other components must be eliminated. However, these interfering effects can be eliminated by application of squaring methods forming mean values from correlation measurement technology and specific comparison methods.

The thermal noise thermometer is suitable for use in cases where conventional electrical thermometers change their properties and cannot be easily removed for recalibration. Thermal noise thermometers are not affected by nuclear radiation and are therefore used in nuclear reactor technology, often in combination with resistance thermometers and thermocouples.

Capacitive temperature sensors

The dielectric constant of most insulating materials is temperature-dependent. If capacitors are made of insulating materials with a dielectric constant dependent to a large extent on the temperature effect, they can be used for temperature measurement. Suitable materials are, for example, triglycine sulphate and barium strontium titanate, which are operated above their Curie point. The temperature dependence of such electrical materials conforms to the Curie-Weiss law. The following applies to the capacitance of a capacitor:

$$C = \frac{K_e}{(T - T_C)} \qquad (2\text{-}31)$$

C = capacitance
K_e = material-dependent constant
T = temperature
T_c = Curie temperature

Ferroelectrical materials are free of hysteresis in their temperature characteristic curves and are therefore more suitable than polymeric materials for temperature measurement. The temperature characteristic curve of a ceramic capacitor is shown in Figure 2.21 as an example.

If a temperature-dependent capacitor is incorporated as frequency-determining component in an oscillating circuit, its output frequency f(T) can be used as temperature-dependent signal.

$$f(T) = K_r \cdot \sqrt{(T - T_C)} \qquad (2\text{-}32)$$

K_r = constant

Capacitors are preferred for temperature measurement on moving parts, because the measuring equipment can be coupled to the oscillating circuit by transmitters without contact in this case.
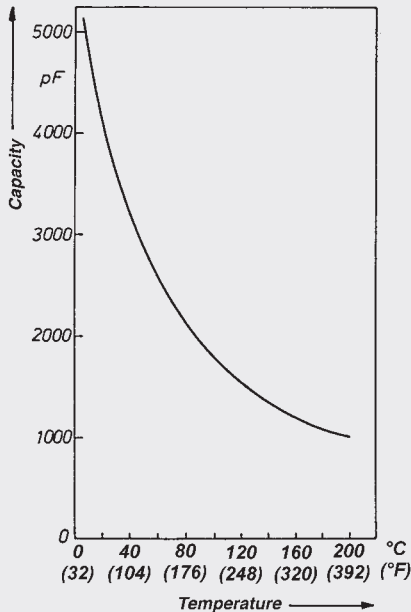
Figure 2.21 Temperature characteristic of a ceramic capacitor with a dielectric of barium strontium titanate

Figure 2.22 Relative frequency change of an oscillating circuit with toroid coil

Another means of measuring temperature is by using the Curie point itself, because specific materials undergo a marked change in their properties in this case. By using this effect, simple two-point controllers can be obtained.

Finally, a summary of the most important temperature measuring instruments, their temperature range, error limits and special features are given in Table 2.3.

Inductive temperature sensors

Temperature-sensitive inductances can also be used for temperature measurement. They are wound, for example, as toroid coils. The coil cores are made of Vicalloy alloys, which are quenched in the liquid phase of the production process and then exhibit a virtually linear increase in the magnetic moment with decreasing temperature.
Such temperature-dependent coils can be incorporated in an oscillating circuit, then the resonant frequency can be used for temperature measurement (Figure 2.22).

Measuring instrument	Temperature range		Error limits	Remote measurement, recording possible?	Special features
	from [°F]	to [°F]			
Mechanical contact thermometers					
Liquid glass thermometer: thermometric liquid non-wetting	(-72)-**36**	**1200**(1800)	see calibration error limits ASME B40.3	no	no additional equipment required.
Liquid glass thermometer: thermometric liquid wetting	-330	410			
Dial thermometers					
Liquid spring thermometer	-30	930	1 to 2 % of the Indication range	yes	no additional equipment required.
Vapour pressure spring thermometer	(-330)-60	660 (1300)	1 to 2% of the scale length	yes	
Rod expansion thermometer	32	1800	1 to 2% of the Indication range	no	
Bimetallic thermometer	-60	750	1 to 3% of the Indication range	recording possible	
Electrical contact thermometer					
Thermocouples Cu-CuN type U, T Fe-CuNi type L, J NiCr-Ni type K, N	-330 -330 0	750 (1100) 1300 (1650) 1800 (2400)	0.75% of required value of temperature, minimum	yes	versatile, signal processing only with additional equipment
PtRh-PT type R, S $PtRh_{20}$-$PtRh_8$ type B	0 0	2400 (2900) 2700 (3300)	0.5% of required value of temperature, minimum	yes	
Resistance thermometers with metal measuring resistors					
Pt resistance thermometer	(-480)-330	1550 (1800)	0.54°F to 8.6°F depending on temperature	yes	
Ni resistance thermometer	-75	480	0.7°F to 3.8°F depending on temperature	yes	
Resistance thermometer with semiconductor measuring resistors					
Hot conductor resistance thermometer, thermistors	(-150)-40 -75 -150	350 (750) 400 750	depending on temp. 0.2 to 2°F 0.1 to 4.5°F	yes	
Cold conductor resistance thermometer	40	400	3.5 to 18°F	yes	Use as limit value switch from
Silicon measuring resistors	-95	350	0.4 to 1.8°F	yes	from 80°F to 350°F
Semiconductor diode/ integrated temperature sensor	-95	320	depending on temp. 0.18 to 5.5°F	yes	
Cryodiodes	-460	270	up to 0.018°F	yes	
Radiation thermometers	-150	6300 (9000)	0.5 to 1.5% of the temperature, but at least	yes	non-contact, low reaction setting times: 0.1 ms to 10 s
Spectral pyrometer	70	6300 (9000)	0.1 to 3.5°F in the		
Bandpass pyrometer	-150	3600	range from -150 to		
Total radiation pyrometer	-150	3600	750°F		
Ratio pyrometer	300	5400			
Thermographic equipment	-60	2700			Measurement of temperature distribution, temperature differences can be resolved to 0.2 °F
Seger cone	1100	3600			indicate whether specific temperatures reached or exceeded
Temperature characteristic bodies	212	2900	approx. 12°F		
Quartz thermometer	-110	480	resolution 0.18 (0.018)°F		digitizable measuring signal, resolution 0.1 mK
Thermal noise thermometer	-450	1800	1‰		high cost
Ultrasonic thermometer		6000	approx. 1%		equipment
Gas thermometer	-450	2000	according to type		scientific thermometer
Optical measuring method					suitable temperature fields
Temperature measuring colours	100	2500	approx. 9°F		
Liquid crystals	-4	160	approx. 2°F		suitable for temperature fields, reversible color change
Fibre-optic luminescent thermometer		750	1°F	yes	not affected by electromagnetic interference, simple explosion protection

Table 2.3 Temperature measuring instruments and special temperature measuring methods

2.3 Industrial direct-contact thermometers

The term **direct-contact thermometer** covers all thermometers which come into direct contact with the medium being measured. Non-contact measuring instruments, such as pyrometers, operate differently and are not addressed here. Direct-contact thermometers are used in production processes for measurement of the process variable "temperature".

Their construction is similar regardless of the sensor type. A direct-contact thermometer consists of the temperature-sensitive element, which is installed in a tube casing - often called a stem - for protection. In many cases the stem has a terminal block at the top end for wiring of the supply leads. This construction is standardized and is considered to be the "measuring element". Measuring elements can be supplied with a thermowell and industrial head. The protective tube and industrial head together form the thermowell assembly. The assembly protects the sensitive measuring element against mechanical and chemical stress as well as the terminals against dirt and moisture.

Figure 2.23   Industrial direct-contact thermometer (electrical)

2.3.1 Temperature measurement with direct-contact thermometers

The **0th law of thermodyamics** is the physical basis of direct-contact thermometry: if two bodies A and B are in thermal equilibrium with a third body C, A and B are also in thermal equilibrium. Thermal equilibrium means that no heat-exchange takes place between the bodies. The temperature of bodies A, B and C is then identical.

Applied to thermometry the 0th law can also be expressed as follows: if the measured medium and thermometer are in thermal equilibrium with their environment, the thermometer is also in thermal equilibrium with the measured medium. This is exemplified, for example, in temperature measurement in a body at room temperature, if the room temperature is constant over time. In this case the measured medium and thermometer settle at the ambient temperature. The heat-exchange between measured medium, thermometer and environment continues until thermal equilibrium is established between all participants. In this condition the measured medium, thermometer and environment have the same temperature; in this case the thermometer measures the true temperature of the measured medium.

In practice, however, often the temperature of the measured medium differs from the ambient temperature and is not constant in time. Strictly speaking thermal equilibrium between measured medium, thermometer and environment is never established, because heat-exchange continuously takes place between the three. If the measured medium temperature exceeds the ambient temperature, thermal conductivity of the thermometer ensures continuous heat removal from the measured medium. Its heat capacity makes the thermometer inert to temperature changes. Poor heat contact between the thermometer and measured medium leads to higher heat transfer resistance and thus to smaller temperature indication. The thermometer also interferes with the temperature distribution within the measured medium.

For these reasons temperature measurements are always subject to larger or smaller errors. These errors are unavoidable, but can be kept

very small by a smart thermometer design. A pre-requisite is a detailed knowledge of the application for which the thermometer is to be used. Direct-contact thermometers for some common industrial measuring applications are described below.

2.3.2 Temperature measurement in liquids and gases

For temperature measurement in pipes and vessels, thermometers with threaded connections or compression fittings generally used, if this is permitted by the maximum temperatures, pressures and flow rates. Common thread sizes are 1/8" NPT, $1/4$" NPT, & $1/2$" NPT. Threaded connections are particularly common with sheathed thermocouples. They have an inner bore and are sized according to the outside diameter and welded or soldered to the thermocouple. Compression fittings allow accurate adjustment of the installation depth during assembly. When the compression fitting is tightened a steel ferrule is tightened on the outer surface (Figure 2.24). This connection is gastight and can be used up to 660°F and 1200 PSI (350°C and 80 bar) with special versions up to 6000PSI (400 bar). However, removal and reinstallation of the thermometer is no longer possible. If a Teflon thrust collar is used instead of the ferrule, this connection method is suitable for up to 400° F and 160 PSI (200°C and 10 bar) and can be loosened again easily. Thermometers assembled with threaded bushes and compression fittings cannot be changed during operation. However, the small space requirement and rapid response time due to the small mass of the stem section are advantageous, in particular for measurements in gases.

Thermometers with thermowells are used under demanding operating conditions such as high pressures, high flow rates, high temperatures and corrosive measured media or also to allow easy replacement of thermometers. Thermowells must have the following properties.
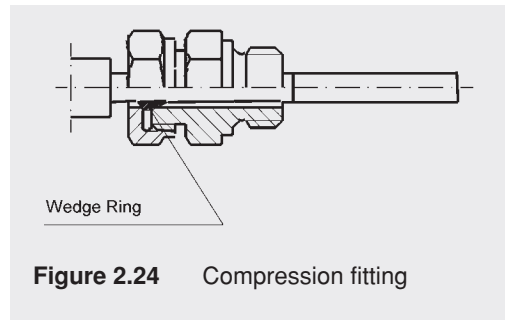
Figure 2.24 Compression fitting

They should:
- be gas tight
- not develop noxious gases themselves
- be insensitive to temperature changes
- not be attacked by the measured medium and
- have a sufficiently high mechanical resistance to pressure, bending, impacts and vibrations within their operating temperature range.

In addition they should have good thermal conductivity to allow short response times, at least in the area of the measuring point.

2.3.2.1 Installation conditions of thermometers

As the above requirements on thermowells are to some extent contradictory, a compromise must always be found to adapt a thermometer as well as possible to its measuring task. This results in a wide variety of thermowell and thermometer designs suitable for the various installation conditions.

Thermometer installation in pipes

When installing thermometers and thermowells in pipes, connection pieces are first welded into the pipe. Thermometers are installed against the direction of flow in pipes with a small diameter (Figure 2.25a).

The thermometer can also be installed vertically in large diameter pipes (Figure 2.25c), if it is assured that the flow-induced periodic separation of vortices do not cause natural vibrations (see Section 2.3.2.2). If there is not adequate space to install the thermometer vertically and it is not possible to mount it into a tee-bend in the pipe, then the thermometer should be mounted at a slant against the direction of the flow (Figure 2.25 b).

Thermometer installation in tanks or cylinders
For pressures up to about 1300 PSI (90 bar) thermowells are threaded into tanks or cylinders. Welded-mounted thermowells are often used at higher pressures. Flanged thermowells are used for temperature measurement in tanks with an inside lining to prevent damage to the tank. The parts of these tubes coming into contact with the measured medium are also often lined for protection against corrosive media.

Thermometer installation in steam pipes

Thermowells are exposed to particularly heavy stresses in the measurement of **steam temperatures**. Sudden condensations, i.e. after changes in cross-section, lead to a sudden load change. Therefore conical thermowells made of solid material and designed according to the requirements are welded into steam pipes. They are substantially more rugged than threaded thermowells and can therefore also withstand higher loads. The thermowells can be welded directly into tanks or cylinders with wall thicknesses greater than 1.4 inches (35 mm). A connection piece (1) is first welded into thin-walled tanks as in pipes (Figure 2.27). The end of the conical thermowell (2) must not be further forward than the inner tanks wall, and for static reasons must never project out of the hole.

Figure 2.25 Installation of thermometers in pipes
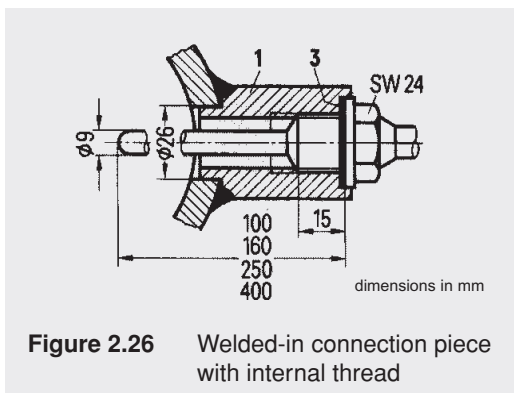
Figure 2.26 Welded-in connection piece with internal thread
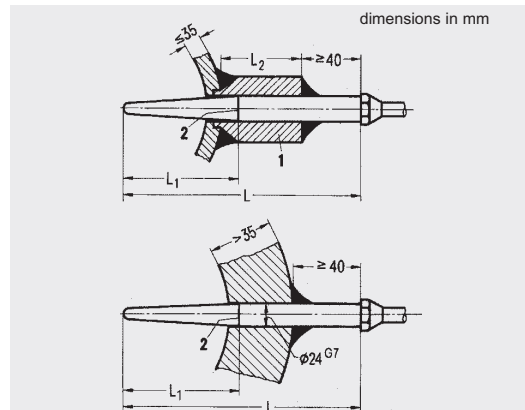
Figure 2.27 Thermometer installation in steam pipes

Thermometer installation in flue gas ducts

Thermometers with a **gastight threaded sleeve** (4) are installed in flue gas ducts; the sealing surface (2) of the reducing sleeve (1) is faced (Figure 2.28). The seal (3) consists, for example, of asbestos. The thermowell is coated and can be made of unalloyed or alloyed steel. If gastightness is not required, stop flanges can also be used for installation in ducts.
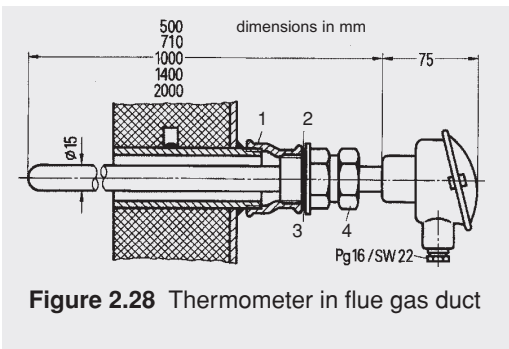
Figure 2.28 Thermometer in flue gas duct

2.3.2.2 Mechanical load

Thermowells are subject to pressure, bending and vibration loads in tanks and cylinders and in particular in pipes. A higher load occurs at the clamping point of a thermowell exposed to a transverse flow, because the highest bending moment is present there. High requirements must be followed on the notch impact strength of the thermowell material because of the notch effect at the clamping point due to unavoidable changes in cross-section. This should be noted particularly at low temperatures, because the notch impact strength of metallic materials diminishes sharply in this case, although the mechanical load generally remains high.

High temperatures require materials with a high creep strength or high time yield limit. When the wrong material is selected the dead weight of the protective tube may already lead to damage. Rapid temperature changes may also cause damage to protective tubes; in this case adequate resistance of the material to temperature changes should be assured. In contrast to ceramic materials, which react very sensitively to temperature changes, metallic materials are not problematic. If the operating conditions require use of a metallic protective tube, materials with a low coefficient of thermal expansion, i.e. quartz glass, must be used. Because many parameters determine the selection of the correct thermowell material, no universally valid statements can be made here. In cases of doubt a strength calculation should always be made.

Strength calculations for thermowells are generally carried out according to the methods of P. Dittrich, ASME PTC 19.3 (Performance and Test Code of the American Society of Mechanical Engineers) or O. Uhrig. If necessary, the selection of the calculation method is determined by specifications of the customer.

P. Dittrich bases his calculations on the fact that a protective tube is put into a three-dimensional stress state by the hydrostatic pressure. Additionally, bending and shear stresses occur during exposure to flow. All stresses are determined in the strength calculation and combined to form a reference stress. This reference stress must bear a ratio expressed by the **safety factor**, which must never be less than 1.7, to the strength parameter of the material.

The following strength parameters are used to determine the safety factors against fracture and deformation:
- at low temperatures the yield point at elevated temperature σ_S or tensile yield strength $\sigma_{0.2}$ is the stress leading to a strain of 0.2%
- at high temperatures either the creep strength $\sigma_{b/100000}$, i.e. the stress leading to fracture after 100000 h, or the limiting creep stress $\sigma_{1/100000}$, i.e. the stress leading to permanent strain after 100000 h.

Static loading by the hydrostatic pressure

A purely static load on a thermowell occurs, i.e. in a tank under pressure. As a result of the static pressure the thermowell is in a three-dimensional stress state caused by axial, radial and tangential stresses.
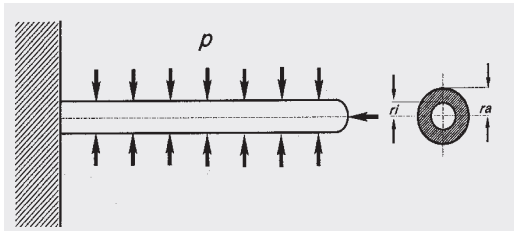
Figure 2.29   Statically loaded thermowell

The inside radius of the thermowell is r_i, the outside radius r_a and p the static pressure acting on the well. To determine the static component of the reference stress the tangential stress s_k for cylinders under outside pressure load according to the empirical formula of Bach is used:

$$\sigma_k = 1.7 \cdot \frac{r_a^2}{r_a^2 - r_i^2} \cdot p \qquad \text{with } \sigma_k \text{ in N/m}^2 \qquad (2\text{-}33)$$

Dynamic loading of a thermowell exposed to flow

If the thermowell is exposed to flow, a dynamic load occurs in addition to the static load.
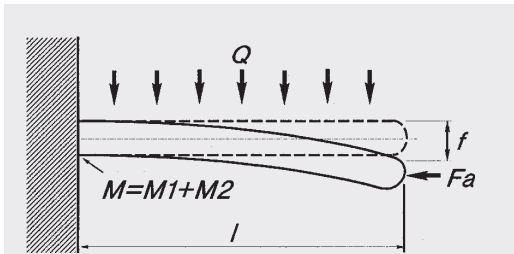
Figure 2.30   Dynamically loaded protective tube

The installation length of the thermowell is l, F_a the axial compressive force, Q the dynamic pressure force and f the bending of the thermowell resulting from dynamic pressure and axial compressive force. The following forces also act on the thermowell exposed to flow:

$$\text{Dynamic pressure force } Q = A \cdot \frac{\rho}{2} \cdot v^2 \cdot \xi \qquad \text{with Q in N} \qquad (2\text{-}34)$$

$$\text{Axial compressive force } F_a = \pi \cdot r_a^2 \cdot \rho \qquad \text{with } F_a \text{ in N} \qquad (2\text{-}35)$$

A is the area exposed to flow (on cylindrical thermowells $A = 2\,r_a \cdot l$), ρ the density of the flowing medium, v the flow velocity and p the static pressure. The resistance coefficient ξ is a dimensionless, empirically determined figure. It takes into account the resistance caused by a cylindrical body (protective tube) in a pipe. ξ is dependent on the ratio of the dynamic area A to the tube cross-section A_R. If this ratio is less than 0.1, ξ can be assumed to be 1. The bending f of the thermowell is now calculated from the dynamic pressure force and the axial compressive force:

Bending:

$$F = \frac{Q}{F_a} \cdot \left(-\frac{l}{2} + \frac{E \cdot J}{l \cdot F_a} \cdot \left(\frac{1}{\cos(l \cdot \sqrt{F_a/E \cdot J})} \right) \right)$$

$$\text{with f in m} \qquad (2\text{-}36)$$

where E is the modulus of elasticity of the material and J the axial geometric moment of inertia. $J = \pi \cdot (d_a^4 - d_i^4) / 64$ applies to cylindrical tubes, d_a and d_i corresponding to the outside and inside thermowell diameters.

The bending moments M_1 and M_2 acting at the clamping point are then calculated from the dynamic pressure force Q and the axial compressive force F_a. The thermowell exposed to flow is treated like a beam with distributed load:

$$M_1 = Q \cdot \frac{l}{2} \qquad \text{with } M_1 \text{ in Nm} \qquad (2\text{-}37)$$

$$M_2 = F_a \cdot f \qquad \text{with } M_2 \text{ in Nm} \qquad (2\text{-}38)$$

In the calculation of M_1 the calculation for welded-in thermowells is made with l and not with l/2 for safety reasons. With the resistance moment W of the thermowell at the clamping point the bending stress σ_b resulting from the inflow is obtained:

$$\sigma_b = \frac{M_1 \text{\textbackslash}M_2}{W} \qquad \text{with } \sigma_b \text{ in N/m}^2 \quad (2\text{-}39)$$

$$W = \pi \cdot \frac{d_a^4 - d_i^4}{32 \cdot d_a} \qquad \text{with W in m}^3 \qquad (2\text{-}40)$$

The total stress of the thermowell exposed to flow consists of the tangential stress σ_k and the bending stress σ_b. When calculating the safety against fracture or deformation the reference stress σ_v is calculated by adding one third of the smaller stress to the larger of the two stresses:

$$1\text{st case}: \sigma_k > \sigma_b \quad \sigma_v = \sigma_k + \sigma_b / 3 \quad (2\text{-}41)$$

$$2\text{nd case}: \sigma_k < \sigma_b \quad \sigma_v = \sigma_b + \sigma_k / 3 \quad (2\text{-}42)$$

$$\text{Safety factor}: \qquad S = \sigma_{permiss.} / \sigma_v \qquad (2\text{-}43)$$

The stress $\sigma_{permiss.}$ is the maximum permissible stress for the material in question, i.e. the strength parameter taking into account the maximum temperature occurring (see tables in Section 2.3.2.4). The safety factor should not be less than 1.9 for cylindrical thermowells and not less than 1.7 for conical ones (according to DIN 2413 and AD Specification D 11).

The procedure shown here reproduces an abbreviated form of the calculation. Compared to the detailed method, which is not described here for space reasons, it always supplies the more conservative results and can be used for liquids and gases. Pressure, temperature and density are related in a way, which is very difficult to measure in the case of steam, so that it is not possible to calculate a thermowell with these simple equations. Therefore thermowells were standardized for typical applications. Load diagrams, which reproduce the operating limits of these thermowells under predetermined operating conditions, are included in the standard (see Section 2.3.2.5).

Vibration load

Vortices periodically separate behind bodies exposed to flow. A **Karman vortex street** is formed. The frequency of vortex separation depends on the geometry of the body and the flow velocity. With cylindrical thermowells exposed to transverse flow this effect should not be disregarded. If the frequency of the vortex separation corresponds to the resonance frequency of the thermowell, the latter vibrates at the same time and may be very quickly destroyed if the vibrations are continuos. A thermowell assembly firmly threaded in at the threaded end forms two systems capable of vibration with two natural frequencies, which originate from the thermowell and neck tube with the connection head at its end. The frequency of the vortex separation in the case of cylindrical thermowells exposed to transverse flow as well as the natural frequency of the thermowell are calculated in the following section. The following equation applies to the frequency of the vortex separation f_w:

$$f_w = St \cdot v / d_a \quad \text{with } f_w \text{ in 1/s} \quad (2\text{-}44)$$

where St is the Strouhal number, v the flow velocity of the medium and d_a the outside diameter of the thermowell. The Reynolds number Re and the Strouhal number St are characteristic numbers from the similarity theory. The Reynolds number takes into account inertia and friction, therefore the kinematic viscosity ν of the medium enters into its calculation. Above Re = 1000 a linear relationship exists between the frequency of the vortex separation and the flow velocity.

$$Re = v \cdot d_a / \nu \qquad (2\text{-}45)$$

The Strouhal number is then constant: St - 0.21. The frequency of the vortex separation can therefore be calculated very easily.

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For calculation of the natural resonance of the thermowell the angular frequencies of the tube w_R and a mass-less bar with a point mass at the end (bottom) ω_B are combined into a resultant angular frequency:

$$\omega_R = \frac{z_n^2}{l^2} \cdot \sqrt{\frac{E \cdot J}{A_s \cdot \rho}} \qquad \text{with } \omega_R \text{ in 1/s} \quad (2\text{-}46)$$

$$\omega_B = \sqrt{\frac{3 \cdot E \cdot J}{\beta \cdot m}} \qquad \text{with } \omega_B \text{ in 1/s} \quad (2\text{-}47)$$

E is the modulus of elasticity of the material and J the axial geometrical moment of inertia. The following applies to cylindrical tubes:

$$J = \pi \cdot (d_a^4 - d_i^4) / 64 \qquad (2\text{-}48)$$

A_s is the cross-sectional area of the thermowell (circular area), l the free length of the thermowell, m the bottom mass, r the density of the material and z_n the coefficient: $z_1 = 1.875$ (fundamental tone, $z_2 = 4.694$ (1st harmonic). The following applies to the resultant angular frequency w:

$$\omega = \sqrt{\frac{1}{1/\omega_R^2 + 1/\omega_B^2}} \qquad \text{with } \omega \text{ in 1/s} \quad (2\text{-}49)$$

and therefore to the resonance frequency f_r of the thermowell:

$$f_r = \omega / 2 \cdot \pi \qquad \text{with } f_r \text{ in 1/s} \qquad (2\text{-}50)$$
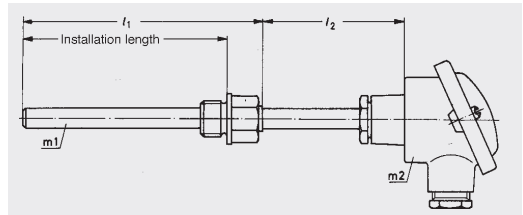
Figure 2.31 Threaded-type Thermometer
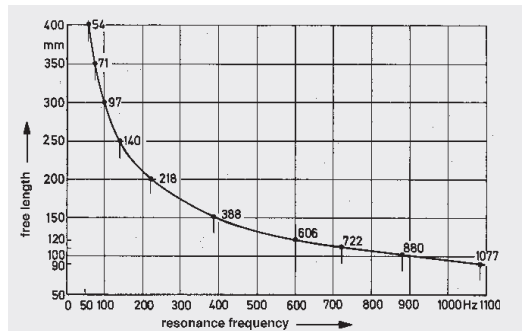
Figure 2.32 Fundamental resonance for cylindrical thermowells made of stainless steel, dia. 0.35 in., 0.04 in. wall thickness

The resonance frequencies represented here may deviate by 10 to 15%. The free installation length is denoted by l_1
An approximate calculation of the natural resonance of the connection head can also be made

l_2	Neck tube 11 x 1			Neck tube 11 x 2			Neck tube 14 x 2.5			dia ø x. wall thickn.	
	GG	AL	K	GG	AL	K	GG	AL	K	Remarks	
145 mm (5.7")	44 42	89 79	104 90	46 44	100 89	114 102	66 59	127 107	159 130	without with	terminal socket
165 mm (6.5")	36 35	75 68	91 75	38 36	83 71	99 85	48 46	101 98	133 111	without with	terminal socket
170 mm (6.7")	35 34	72 66	88 74	36 34	79 70	96 82	47 45	99 95	128 110	without with	terminal socket

Table 2.4 Head resonances of thread-in thermometers in Hz
GG denotes grey cast iron, $m_2 = 0.59$ kg, AL aluminium, $m_2 = 0.13$ kg, K plastic, $m_2 = 0.08$ kg. l_2 is the neck tube length

according to equation 2-47 by disregarding the neck tube mass. Table 2.4 shows resonances of commercially available connection heads in conjunction with typical neck tubes.

Note
The formulas specified in this section for the calculation of resonance frequencies apply to cylindrical thermowells. For conical thermowells, i.e. type D, 2-46 and 2-47, they are suitably supplemented. Despite the apparently simple calculation methods for the frequency of the vortex separation and the resonance frequencies it is seldom possible to determine the actual resonance frequencies of the thermowells, because a measuring element, which leads to interference with the resonance sharpness and a change in the resonance width, is also present inside the tube. Furthermore, the life of thermowells is impaired by details such as the type of thread and notches at cross-section changes, which are not taken into account in the calculation. For this reason the frequency of the vortex separation should always be less than 80% of the fundamental resonance of a protective tube according to Murdock. In cases of doubt a vibration test should always be conducted. The thermowell is clamped under real conditions on the vibrating table and excited sinusoidally or with noise frequencies. This is the only way that the resonance points can be accurately determined and the thermowell subjected to a continuous load test including the effect of temperature.

2.3.2.3 Chemical resistance

Contact thermometers are in direct contact with the medium to be measured, therefore thermowell materials must be capable of withstanding the chemical attack of the medium as long as possible. Chemical attack takes place in three typical ways, which are briefly described below:

Resistance in oxidizing atmosphere

Metallic materials oxidize in air. Unalloyed steels oxidize above 900°F to 1100°F (500°C to 600°C), scale-resistant high-temperature CrAl steels above 1800°F (1000°C). With increased mechanical loading such as high flow rates and high pressures, Co- or Ni-based high-temperature alloys have proven effective. The temperature resistance of these high-temperature alloys is based on the formation of strongly adhesive oxide films on their surfaces, which prevent the oxidation process from penetrating further into the interior of the material. Particles in the measuring medium, in flue gases, i.e. ashes and soot, lead to local damage to the oxide films, which cause mechanical erosion. Carbide coatings provide a solution in this case for temperature up to 1000°F (550°C). Noble metals such as platinum or platinum-rhodium alloys and ceramic materials are used above 1800°F (1000°C). Type 610 or 710 (gastight) aluminum oxide ceramics are commonly used up to 3300°F (1800°C).

Resistance in cases of oxygen deficiency and in reducing atmosphere

Hydrogen already penetrates the metal structure of the thermowell material at low temperatures. The results are embrittlement and fracture under mechanical load. A remedy is provided by steel alloys containing titanium and molybdenum which are resistant to high pressure hydrogen. The embrittlement of metallic materials by carbon can be explained by carburization. As in the hardening of steels, carbides form during carburization; the thermowell is fully nitrided. The consequence is the loss of toughness, which leads to fracture during vibration and shock. Sulphur damages nickel-based thermowell materials above 1100°F (600°C). Sulphides deposit along the grain boundaries. These deposits are not only limited to the surface, but spread into the interior of the thermowell over time. Thermowells are particularly endangered by introducing gases containing Sulphur.

Resistance in aqueous media

Continuous surface erosion by acids and alkali's on metallic materials in aqueous media leads to destruction, therefore glass and quartz thermowells are used here under low mechanical

loads. High mechanical loading requires coated metallic thermowells. Whereas plastics such as Teflon are used at low temperatures, enamel is often used at high temperatures. In weak acids corrosion-resistant austenitic steels have proved effective, in stronger acids Ni- and Co-based alloys such as Monel.

In the event of strong chemical attack and high temperatures, metallic thermowells are provided with noble and sintered metal coatings, such as platinum and tantalum. It should be noted that in the long term electro-deposited coatings tend to form hairline cracks because of their small thickness and different coefficients of thermal expansion, and are therefore inapplicable. A durable

coating can be achieved by electrolytic deposition, i.e. of tantalum and platinum from the salt melt.

In aqueous media, corrosion by cell formation may occur if different metals come into contact with an electrolyte. Compared to the more noble metal the less noble material is the solution electrode. For example with a nickel-plated iron tube the smallest pore in the nickel leads to dissolution of the iron.

Chemical attack may take place in the most diverse ways, so it is always preferable to use the same material for both the thermowells and the system into which they are subsequently installed.

2.3.2.4 Commonly used materials for thermowells

Material-number	Yield point at elevated temperature σ_s (psi x 100)			t_{max} in °F	Application
	68°F	1100°F	1800°F	in air	
Brass	500	-	-	750	General application, electric furnaces, gas furnaces, enamelled fittings for flue gas thermometers and baths containing zinc
AISI 430 AISI 446	710 to 930 710 to 930	42 42	1.0 1.0	1900 2200	Waste gases containing sulphur, corrosive and oxidizing atmospheres, electric and gas furnaces
AISI 314	850 to 1100	171	2.2	2200	Oxidizing atmospheres without sulphur
Brightray B	970 to 1200	113	5.8	2100	Baths containing salt, lead, barium and chlorine
Inconel 600 AISI B 163	812 to 1000 780 to 1100	123 189	6.5 5.8	2000 2100	Pressure-resistent fittings for furnaces and reactors up to 1650°F

Table 2.5 Survey of mechanical strength of steels for thermowells

Material Type	Limiting creep stress $\sigma_1/100\,000$ (psi x 100)					$t_{max,}$ °F	Application
	68°F	850°F	930°F	1000°F	1100°F		
AISI A204	640 to 830	316	149	45	-	1000	Weld-in thermowells for steam pipes
AISI A182-F11	640 to 850	426	242	83	29	1000	Weld-in thermowells for steam pipes
AISI A182-F22	640 to 850	-	213	107	57	1060	Weld-in thermowells for steam pipes

Table 2.6 Survey of mechanical strength of high-temperature steels for thermowells

Material Type	Tensile yield strength $\sigma_{0,2}$ (psi x 100)					Application
	68°F	400°F	600°F	750°F	900°F	
304	268	184	160	142	133	Food industry and medical equipment
321	297	225	197	181	173	Food industry, photo and chemical industry
347	297	225	197	181	173	
316Ti	326	239	210	196	187	Chemical industry, photo, paint, varnish and synthetic resin production
316Cb	326	239	210	1196	187	Chemical industry, paint and rubber production

Table 2.7 Survey of mechanical strength of stainless steels for thermowells.
A table of chemical resistances of steels to the most diverse corrosive media is included in the Appendix, Section 5

2.3.2.5 Standardized thermometers

Thermometers for typical applications are standardized under ASME B40.3. They in turn are used with standardized components such as thermowells (ANSI B16.5). The design of the thermowells is important for the specific application.

To aid the user with the design and material selection, particularly for critical applications, i.e. temperature measurement in steam pipes, the critical parts of thermowells are standardized. The standard specifies dimensions, materials, operating temperatures, flow rates, marking and tests. In addition, load diagrams are included which specify the operating limits for the temperature and pressure of the thermowell in question as a function of its material, the flowing media and the dimensions.

Standardized thermowells

Written standards for thermowells for thermometers are currently under development by ANSI/ASME. These standards will cover thermowells for use in applications such as temperature measurement in gases, vapors and liquids under pressure in pipes and vessels. For flanged thermowells, the standards for the flanged portion are already documented in ANSI/ASME B16.5.

European DIN standards already exist for thermowells and they specify several different types of thermowells; types A,B,C,D, E, F & G as described below. Since their design is similar to the U.S. versions, emphasis will be placed on the European thermowell standards:

Type A
Enameled thermowells for flue gas thermometers made of steel, for pressures up to 15 PSI (1 bar) and temperatures up to 1000°F (550°C) for use in waste gas ducts, furnaces, air ducts and open channels. The wells can be mounted i.e. with a stop flange.

Type B
Thermowell with metric or equivalent threads for thermometers made of different materials. The materials are selected according to the measuring conditions from the table specified in the standard. The thermowell is used up to a max. pressure of 1000 PSI (75 bar) in liquids, vapors and gases. The maximum tightening torque on threads is 37 ft.-lbs.
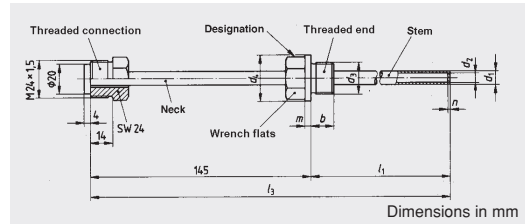
Figure 2.33   Thermowell with threaded connection, Type B
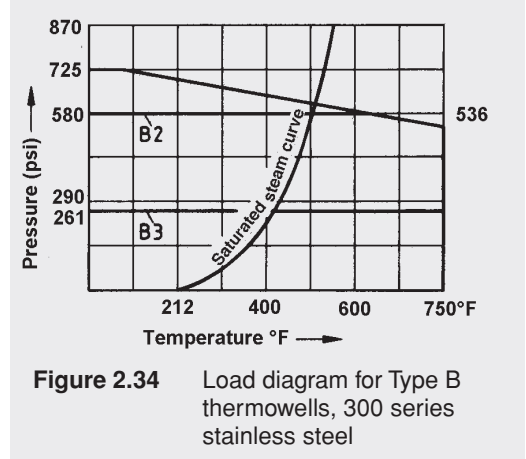
Figure 2.34   Load diagram for Type B thermowells, 300 series stainless steel

The designations B2 and B3 relate to installation lengths (l_1) of 250 and 400 mm; the wall thickness of the thermowell is 1 mm. The maximum flow rate for air and superheated steam is 25 m/s , for water 3 m/s.

Type C
Thermowell with 1" metric or equivalent threads for thermometers made of different materials, which are selected according to the measuring conditions from the table specified in the standard. The thermowell is suitable for use up to a max. pressure of 2000 PSI (120 bar) in liquids, vapors and gases. The tightening torque on the threads is 74 ft.-lbs.
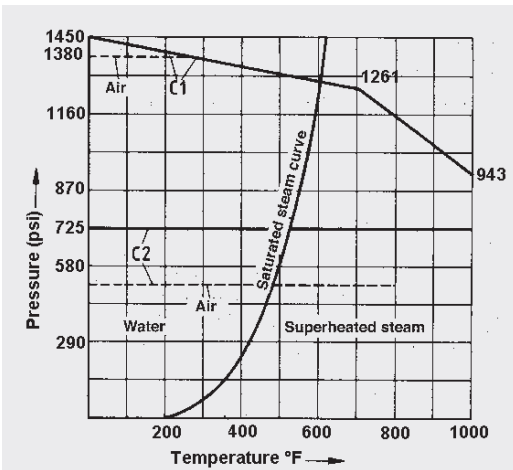
Figure 2.35   Load diagram for type C thermowells, made of 300 series stainless steel

Figure 2.37   Load diagram for thermowells, type D made of 1.7335

The designations C1 and C2 relate to installation lengths (l₁) of 160 and 250 mm; the wall thickness of the thermowell is 2 mm. The allowable flow rate for air and superheated steam is 40 m/s, for water 5 m/s. The maximum operating temperature of the materials 316SS and 304SS is 750°F (400°C) in this case.

Type D
Weld-in thermowell for thermometer made of different materials, which are selected according to the measuring conditions from the table specified in the standard. Weld-in thermowells are suitable for use under high pressure and high flow rates in liquids, vapors and gases.

Figure 2.36 Weld-in thermowell, type D

The designations D1 to D5 specify installation length (l₁) and thermowell length (l₃). The maximum flow rate for air and superheated steam is 60 m/s, for water up to 450 bar 5 m/s.

The DIN specification requires that only materials with an acceptance certificate according to DIN 50049 may be used for the thermowells and that they are made from one piece. The semi-finished product must be inspected to ensure that it is free of cavities and cracks before processing. The surface of the conical section (l₁) may have a maximum roughness depth of 1.6 μm. The finished thermowell must be pressure-tested without neck tube at 500 bar (7500 PSI). During welding the cylindrical part of the shank must not project into the measuring space. When used in steam it should be ensured that the load capacity up to the critical point is limited by the steam pressure curve. At pressures above the critical point the maximum temperature is the critical temperature (375°C, dot-dash line in the load diagram). Towards higher temperatures the load capacity is characterized by the specified curve obtained from strength calculations.

Type E, F and G

Thermowells with a tapered shank for shorter response times for use in gases and liquids at pressures of up to 100 bar (1500PSI) in pipes and vessels. Type E is mounted with a cutting ring threaded connection, type F by a flange and type G with a G 1 A thread.
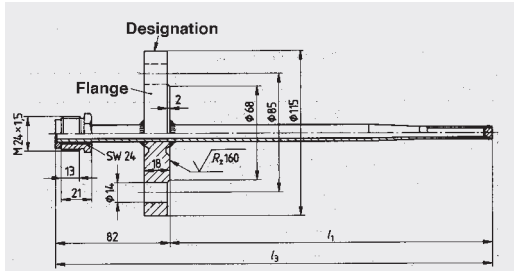
Figure 2.38 Flanged thermowell, type F
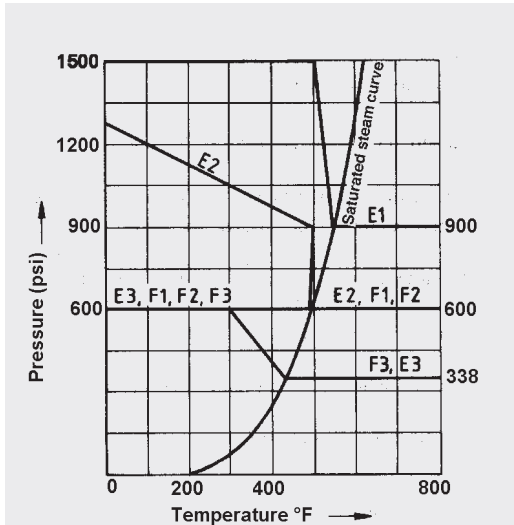
Figure 2.39   Load diagram for thermowells, type E and F made of 304SS & 316SS

The designations E1/F1 to E3/F3 relate to installation lengths (l_1) of max. 225, 285 and 345 mm. The wall thickness of the thermowell must not be less than 1.45 mm at any point on the conical tran-

sition section. The maximum permissible pressure for type F is 40 bar due to flange PN 40. In the case of PN 100 flanges the load data for type E apply. The maximum flow rate for superheated steam is 40 m/s, for water 5 m/s. The max. flow rate is specified as a function of pressure, temperature and installation length in the case of air. The following apply, for example, at 400°C and 40 bar: F1 up to 40 m/s, F2 up to 30 m/s and F3 up to 20 m/s.

European DIN 16179 describes thermowells for machine glass thermometers and dial thermometers and specifies their dimensions, types and materials. A distinction is made between types BD, BE and BS for thermometers with threaded ends and CD, CE and CS for thermometers with a lock nut.
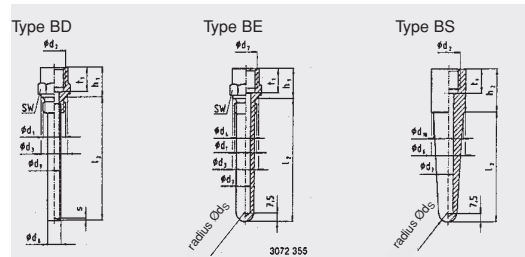
Figure 2.40   Thermowell types BD, BE and BS
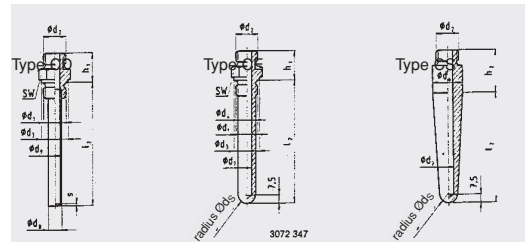
Figure 2.41   Thermowells of type CD, CE and CS

Type BD and CD

Thermowells with threads (d_1) M 18 x 1.5, M 20 x 1.5, M 27 x 2, G 3/8 A, G 1/2 A and G 3/4 A. Thermowells of these types are cylindrical and are made up of several components joined and welded or brazed to each other. They are made of

brass for use at operating pressures up to a maximum of 400PSI (25 bar) and an operating temperature of 160°C. Steel protective tubes may be used up to 40 bar and 300°C, stainless steel ones up to 400°C.

Type BE and CE
Thermowells with threads (d_1) M 18 x 1.5, M 20 x 1.5, M 27 x 2, G 3/8 A, G 1/2 A and G 3/4 A. Thermowells of these types are cylindrical and made of solid material. They are made of brass for operating pressures up to a maximum of 64 bar and an operating temperature of 160°C. Stainless steel thermowells may be used up to 150 bar and 400°C, thermowells made of stainless steel, material No. 1.7335, up to 160 bar and 560°C.

Type BS and CS
Weld-in thermowells made of solid material. The maximum operating pressures and temperatures as well as the required materials is equal to those specified for type BE and CE.

Thermowells of these six types are made for thermometers with immersion tube diameters of 6, 8, 10, 12 and 13 mm. With 12 and 13 mm diameter only M 27 x 2 and G 3/4 A threads are possible for screw-in thermowells. The other dimensions and in particular the thermowell lengths l_2 corresponding to the installation lengths l_1 of the thermometers used are shown in Tables 1 and 2 in DIN 16179. The solid material used for production of thermowell BE, CE, BS and CS must be free of cracks and cavities.

Standardized connection heads

The connection head of a thermowell assembly contains the terminal socket of the resistance thermometer or thermocouple measuring element and possibly also the temperature transmitter. It protects the socket against ambient effects such as dirt, dust and moisture. On thermowells with a long neck tube and heavy metallic connection head, i.e. cast iron, the vibration behavior of the entire thermowell assembly may be changed and break the neck tube due to *head resonances* (see Section 2.3.2.2). Connection heads are standardized in European DIN 43729. The standard distinguishes between types A and B and allows cast iron, aluminum and plastic as material. The standard completely specifies all design details of the connection head. However, connection heads that deviate from this standard have been known to be effective. Therefore, the new version of DIN 43729 will specify only the essential data for universal application of the connection heads. Minimum values are specified for the space requirement of the connection socket, maximum values for the overall height. Details such as the cover lock are left to the designer.
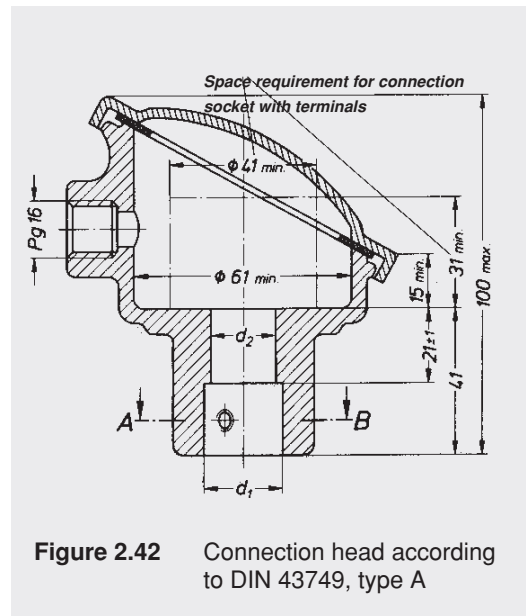
Figure 2.42 Connection head according to DIN 43749, type A

Connection head type A with dimensions (d_1) 12, 24 and 32 mm for assembly with smooth holding or thermowells. Two screws are used for clamping (Fig. 2.42).

Figure 2.43   Connection head according to DIN 43749, type B
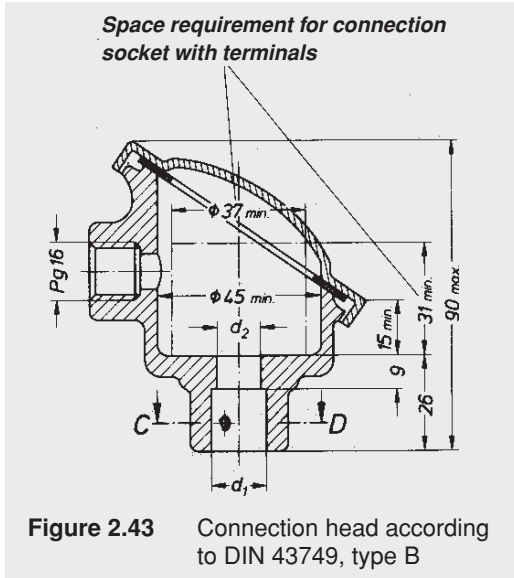
Connection head, type B with nominal dimensions (d_1) 15 mm and M 24 x 1.5 for assembly with smooth holding or thermowells or thermowells with threaded bush M 24 x 1.5.

2.3.3   Temperature measurement in solid bodies and on surfaces

2.3.3.1   Thermometer installation in solid bodies

Holes must be drilled to install the thermometer for temperature measurement in solid bodies. Holes and thermometers interfere with the temperature field within the body and lead to measuring errors. The measuring errors are greater the larger the hole diameter is in relation to the body dimensions, the less deep the hole is in relation to its diameter and the more the thermal conductivity of the installed thermometer differs from that of the body. When measuring the temperature in

bodies with good thermal conductivity the diameter/depth ratio of the hole should be at least 1:5, in bodies with poor thermal conductivity between 1:10 and 1:15.

A general rule is that the temperature sensor must always be installed with direct thermal contact in the hole and the air gap between the hole and thermometer should thus be kept as small as possible. If temperatures up to 350°F (180°C) are measured, heat transfer compound can be used to improve the heat transfer.

In bodies with poor thermal conductivity only thermometers with small heat dissipation should be used. Incorrectly mounted thermometers do not interfere much with the temperature field in bodies with good thermal conductivity, but large measuring errors may occur in bodies with poor conductivity. Only thin thermocouples (thermal wires), i.e. 0.004 dia. X 0.20 in . deep or 0.04 dia. x 2.0 to 2.4 in. deep, which are preferably placed on an isotherm, can usually be installed in small bodies.

Figure 2.44   Temperature measurement in solid bodies
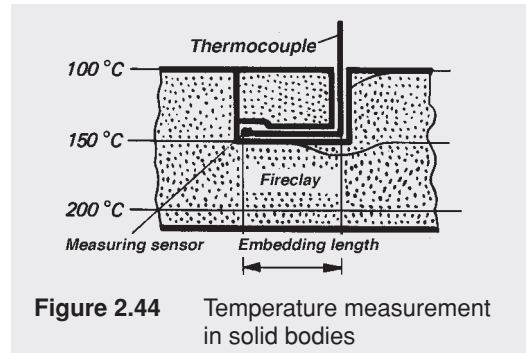
Figure 2.44 shows temperature measurement with a thermocouple in substances with poor thermal conductivity. Heat also flows away through the wires in this case, but only from points on the body being measured which are sufficiently far from the measuring point. Therefore the heat dissipation through the thermocouple hardly interferes with the ambient temperature of the measuring point.

2.3.3.2 Temperature measurement on surfaces

Temperature measurements on surfaces are problematic because each body surface continuously exchanges heat with its environment if the ambient temperature deviates from its temperature. It must therefore be ensured that the heat exchange between thermometer and surface is particularly good and that between thermometer and environment particularly small, preferably just as small as that between body and environment. It should generally be ensured that the temperature sensor is in thermal contact with the surface. On poor conductors and in particular rough surfaces, heat-transfer compound is recommended up to 350°F (180°C) as an intermediate carrier. To prevent measuring errors as a result of the effects of radiation when the temperature sensor is installed, its emission behavior should preferably be the same as that of the surface being measured. Heat dissipation through the thermometer also causes measurement errors. To minimize this effect, the thinnest possible thermocouples are used, which are preferably placed along a surface isotherm. The point at which the temperature is conducted from the surface through the thermometer is thus distant from the measuring point and the measuring error greatly reduced. Thin-walled sheathed thermocouples with small diameters (<0.02 inches) meet the above-mentioned requirements in most cases. It is possible to press these thermocouples firmly on the measured surface, to caulk them in the surface or weld them to the surface. Small metal plates made of good heat-conducting material, i.e. copper, can also be pressed or soldered on to rough surfaces and materials with poor thermal conductivity. The thermocouple is then mounted on the metal plate. Both the contact area and the heat exchange are thus increased and lowering of the local temperature by heat removal at the measuring point reduced.

Resistance thermometers can also be used on larger surfaces, i.e. of pipes and vessels. They are threaded on to the surface or clipped on to pipe surfaces.
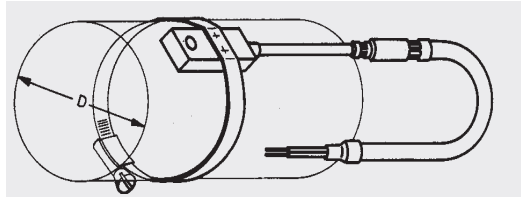
Figure 2.45 Temperature measurement on pipe surfaces

2.4 Temperature measurement variables

2.4.1 Heat transfer from the process to the thermometer

2.4.1.1 Thermal conductivity of substances

If a temperature measuring point is sited at point X in a production process, the following questions should be clarified in the planning and design of this measuring point.

a) How can the temperature be measured with sufficient accuracy at point X without considerable interference with the temperature distribution and thus the process?
b) Is the mean temperature in the environment of point X also to be measured or is the measurement to be made only at "point X"?
c) How accurately can the temperature be measured despite the size of the protective tube and measuring element?
d) What temperature change in time is to be measured with this thermometer? (see Section 2.5)

Temperature measurement requires that the heat energy from the process is transferred via the protective tube and measuring element into the measuring sensor. Therefore the **thermal conductivity** or **heat resistance** of the materials used is very important.

Heat energy transfer can be compared with the transfer of water. The physical concepts involved in temperature measurement have equivalent concepts in water pressure measurement. For example, the temperature corresponds to the water pressure and the heat resistance of a material to the flow resistance of a water pipe.

In the same way that different pipes carry water more or less effectively, each body or material conducts the heat more or less effectively. The **specific thermal conductivity** l corresponds to

the thermal power P_Q, which is carried per cross-sectional area A through a 1 m long bar, the start and end of which are maintained at a 1 K temperature differential. The **specific heat conduction resistance** is 1/l.

Specific thermal conductivity

Figure 2.46 Definition of specific thermal conductivity
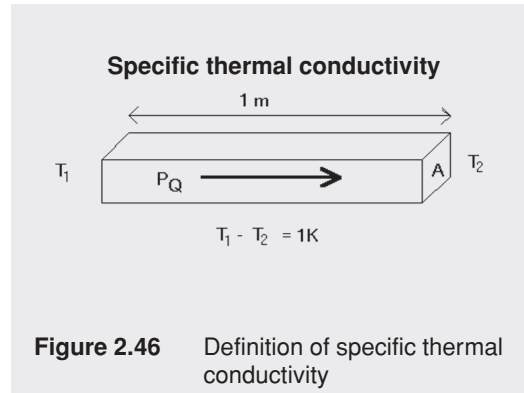
The thermal power carried through a bar is

$$P_Q = \lambda \cdot \frac{A}{l} \cdot \Delta T \quad \text{with} \ \Delta T = T_1 - T_2 \quad (2\text{-}51)$$

where

P_Q	=	transported thermal power
λ	=	specific thermal conductivity
l	=	bar length
A	=	cross-sectional area of the bar
T_1	=	temperature at the 1st end of the bar
T_2	=	temperature at the 2nd end of the bar

It can be seen in the following Table 2.8 showing the specific thermal conductivity of metals, solids, gases and liquids, that the differences between the materials may exceed a factor of 10000.

Material	Thermal conductivity λ [W/(m·K)]
Pure materials	
Acetylene	0.021
Alcohol	0.170
Aluminum	204
Asphalt	0.76
Petrol	0.130
Lead	35
Enamel	1.34
Glass	0.81
Graphite	120 to 150
Rubber	0.16
Igelit (PVC foil)	0.16
Carbon block	1.6 to 4.7
Copper	408
Leather	0.15
Air	0.026
Nickel	60
Oppanol	0.27
Platinum	71.2
Porcelain	1.7 to 3.5
Propane	0.018
Glass	1.34
Mercury	10.0
Sand (dry)	0.58
Silver	432
Steel (unalloyed)	52
Steel (X 12 CrNi 188)	14
Tantalum	54.5
Water	0.060
Brick (dry)	1.0
Tin	65
Contamination	
Boiler scale, gypsum	0.6 to 2.3
Boiler scale, silicate	0.08 to 0.18
Soot, dry	0.035 to 0.07
Coal dust, dry	0.11
Ice	1.75 to 2.3
Cooling water gelatin layer	0.35
Brine gelatin layer	0.46
Salt	0.6
Snow (as hoar-frost)	0.16

Table 2.8 Specific thermal conductivity

2.4.1.2 Heat transfer resistance at interfaces and phase boundaries

Heat cannot continue to flow unimpeded at the interfaces between different materials or phases. The heat transfer resistance of this interface is dependent on the surface structure, the geometry of the sensor, the flow conditions and the different thermal conductivity of the materials or phases. The transferred thermal power in this case is

$$P_Q = \alpha_K \cdot A \cdot \Delta T \quad \text{with} \quad \Delta T = T_1 - T_2 \qquad (2\text{-}52)$$

where

P_Q	=	transported thermal power
α_k	=	specific heat transfer coefficient
A	=	interface of the materials or phases
T_1	=	temperature of the 1st material
T_2	=	temperature of the 2nd material or phase

The **heat transfer coefficient** α_k is dependent not only on the type of medium or material used like λ, but also on the individual geometrical and process factors such as thermometer diameter, velocity, viscosity, pressure, angle of incident flow and absolute temperature of the measured medium.

A completely individual calculation is generally not possible. Therefore reference is made to the specific transfer coefficients α_{nL} and α_{nw}, which were determined for tubes exposed to a transverse flow in air or water at 68°F (20°C).

For water, α_{nw} is independent of the pressure within wide limits at 68°F. Representation with respect to flow rate and tube diameter is sufficient.
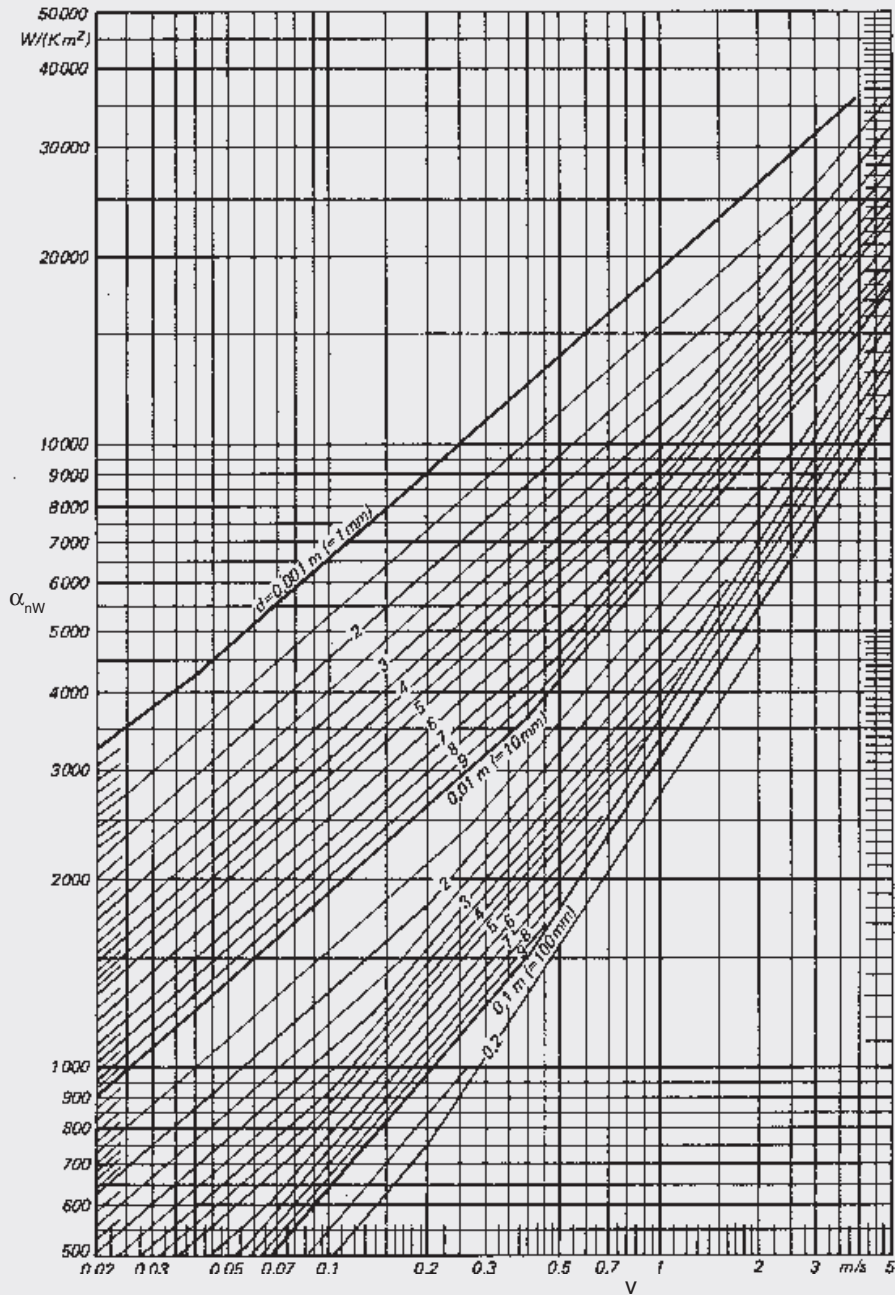
Figure 2.47   Heat transfer coefficient for water at 68 °F (20°C)
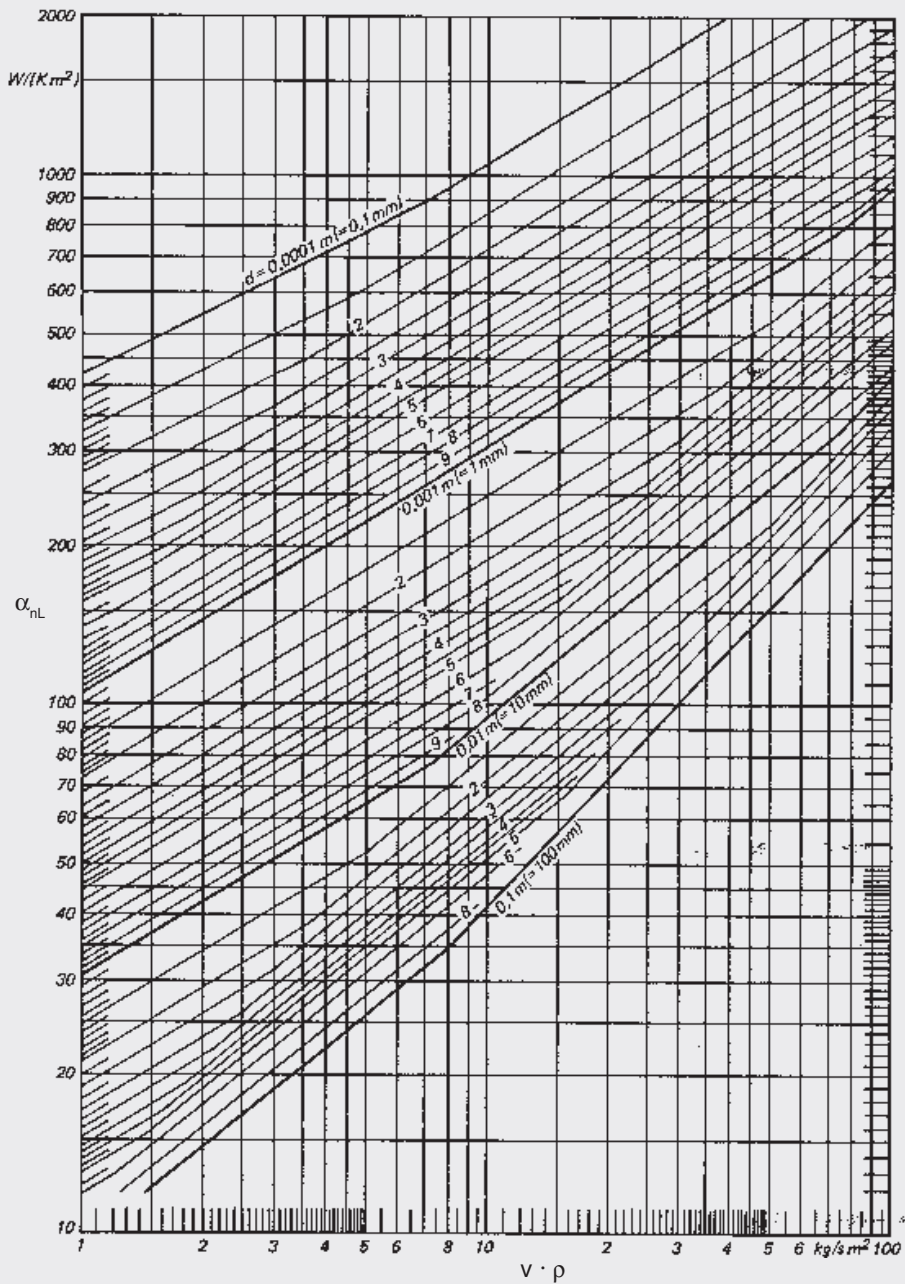
Figure 2.48   Heat transfer coefficient for air for tubes exposed to transverse flow at 68°F

The mass flow per second, and not the velocity, is the important measure for the heat transfer coefficient α_{nL} in the case of air. The mass flow per second is represented by the product of the relative density ρ [kg/m³] with the velocity v [m/s]. The density is dependent on the pressure and temperature. The density can be approximately calculated for pressures less than 1500 PSI (100 bar) and a temperature below 300°C:

$$\rho(p, T) = 374{,}19 \, \frac{p}{T} \qquad (2\text{-}53)$$

ρ = density
p = pressure
T = temperature in K

The diagram above (Figure 2.48) shows the heat transfer coefficient of air at 70°F.

The actual measuring conditions are compensated for by correction factors, by which the heat transfer coefficient for water or air is multiplied:

$$\alpha_W = C_t \cdot C_\beta \cdot C_{be} \cdot \alpha_{nw}$$
$$\alpha_L = C_\beta \cdot C_{be} \cdot \alpha_{nL} \qquad (2\text{-}54)$$

C_t = correction factor for the water temperature (see Figure 2.49)

C_β = correction factor for the angle of incident flow (see Table 2.9)

C_{be} = correction factor for coating and/or contamination of protective tube (see Figure 2.50)

Figure 2.49 Correction factor c_t for water temperature
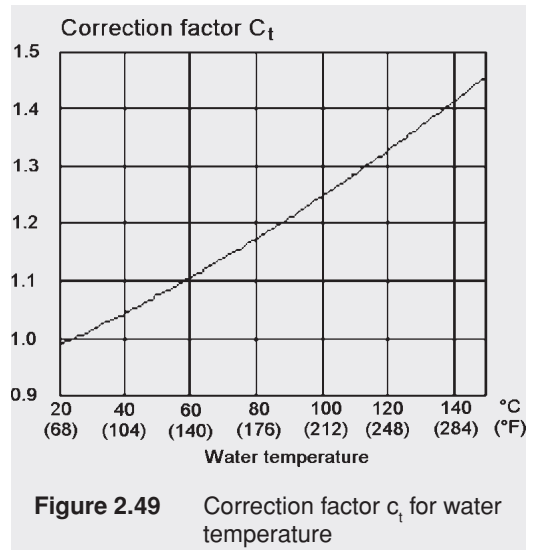
β (°C)	80°	70°	60°	50°	40°
β (°F)	176°	158°	140°	122°	104°
C_β	1.0	0.99	0.95	0.86	0.75

Table 2.9 Correction factor for angle of incident flow β

A thermometer is often supplied with an anti-corrosion coating to prevent deposits of dirt, soot or oxide on the thermometer. The coating thickness **s** and thermal conductivity λ of the coating (see Table 2.9) define the heat transfer to the thermometer. The value of the heat transfer coefficient α_0 of the thermometer, which would result without a coating, also influences the effect of the protective coating. The correction factor can be read from Figure 2.50 with **s**, λ and α_0.
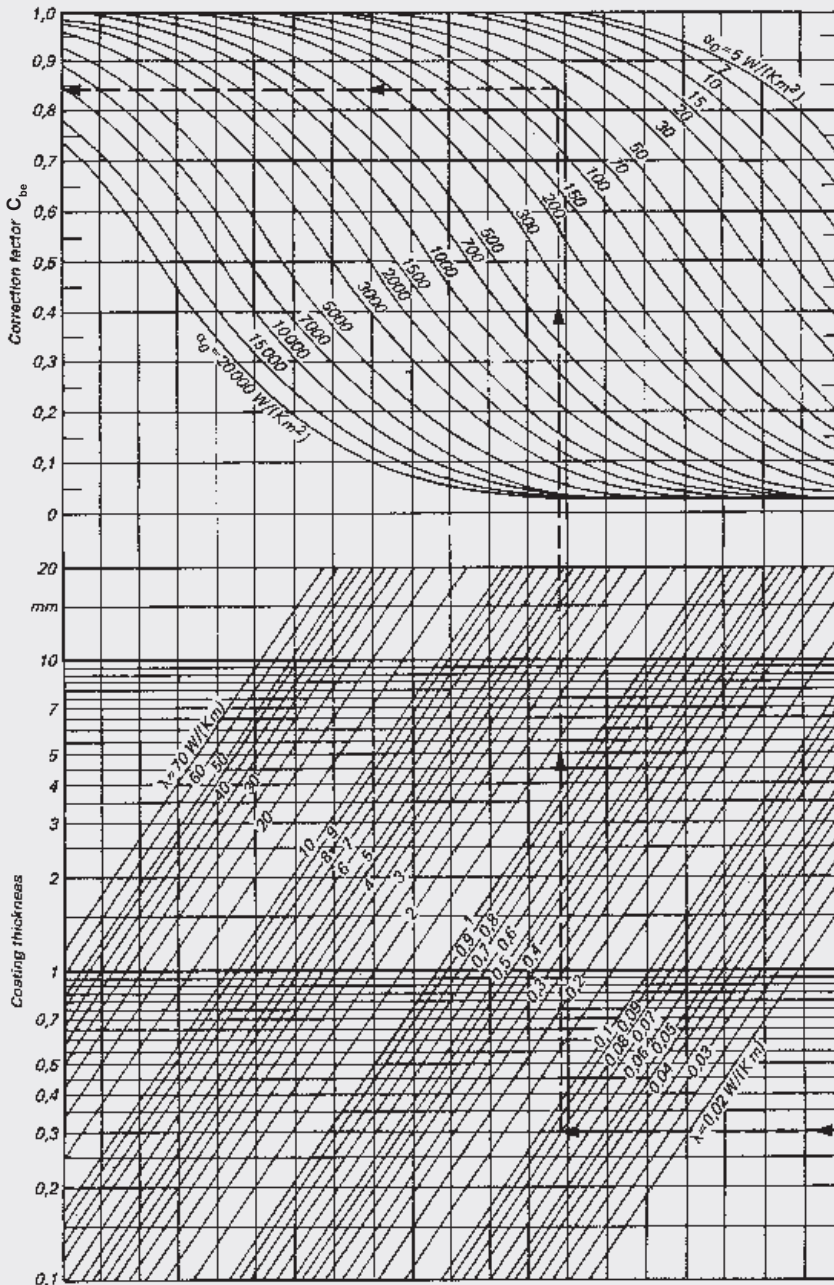
Figure 2.50   Correction factor for coatings and contamination

Measurement in a substance other than air or water

A conversion factor can be determined for measurements in other substances for calculating the heat transfer coefficient:

$\alpha_F = a_F \cdot \alpha_w$ for liquid *(2-55 a)* $\alpha_G = a_G \cdot \alpha_L$ for gases *(2-55b)*

a_F and a_G can be taken from Table 2.10.

Substance	-100°C[1] -150°F	-50°C[1] -60°F	0°C 32°F	20°C / 68°F for liquids 25°C / 77°F for gases	50°C 120°F	100°C 212°F	200°C 400°F	300°C 570°F	500°C 930°F
Hydrogen	8.89	9.99	10.9	11.1	11.2	11.1	10.8	10.4	10.4
Carbon monoxide	0.82	0.89	0.99	0.98	0.96	0.96	0.95	0.95	(0.95)
Nitrogen	0.87	0.97	1.02	1.02	1.02	1.02	1.02	1.01	1.01
Flue gas (from lighting gas without excess air)	—	—	—	1.03	1.04	1.05	1.05	1.05	1.05
Nitrogen (300 bar)	(1.89)	(1.62)	1.47	1.38	1.34	1.24	1.15	(1.11)	(1.03)
Methane	1.36	1.55	1.77	1.83	1.88	2.00	(2.29)	(2.52)	(3.00)
Ethylene	0.83	0.89	1.07	1.13	1.18	1.27	(1.41)	(1.58)	—
Carbon dioxide	—	0.63	0.71	0.73	0.77	0.80	0.85	0.88	1.01
Ammonia	—	1.36	1.41	1.44	1.48	1.55	1.67	1.75	1.85
Propane	(0.39)	(0.46)	0.99	1.07	1.12	1.26	(1.45)	(1.65)	—
Butane	(0.38)	0.41	0.44	1.08	1.17	(1.32)	(1.50)	(1.73)	—
Water vapour	—	—	—	—	—	1.28	1.26	1.33	1.48
Methane	—	0.37	0.48	0.41	0.36	1.07	1.18	(1.28)	—
Ethanol	(0.14)	0.23	0.38	0.29	0.27	1.12	1.24	1.37	—
Carbon tetrachloride	—	—	0.29	0.25	0.22	0.43	0.44	0.44	(0.45)
Benzene	—	—	—	0.29	0.26	0.93	1.17	1.26	—
n-heptane	—	0.32	0.37	0.31	0.27	1.16	1.40	(1.50)	—
Diphyl. (Dowtherm)	—	—	—	0.16	0.17	0.18	0.21	—	—
HT oil	—	—	—	0.10	0.11	0.12	0.15	0.19[2]	—
Ethyl glycol 25% by weight	—	—	0.71	0.72	0.75	—	—	—	—
Hydrochloric acid 30% by weight	—	—	0.71	0.64	0.60	—	—	—	—
Sulphuric acid 96% by weight	—	—	—	0.26	0.29	—	—	—	—
Soda lye 50% by weight	—	—	(0.28)	0.31	0.40	—	—	—	—
MgCl₂ 20% by weight	—	0.50[3]	0.69	0.70	—	—			

[1] The conversion factors for -100°C (-150°F) and -50°C (-60°F) refer to water and air at 0°C (32°F)

[2] referred to water at 200°C (400°F)

[3] at -20°C (-4°F)

a_F is on the left of the dividing line, a_G on the right

Table 2.10 Conversion factors for measured substances

2.4.1.3 Transfer of heat by radiation

Only heat transfer through the material or in direct contact with the surfaces between measured substance and thermometer was explained in Sections 2.4.1.1 and 2.4.1.2. **Thermal radiation** is another form of heat transfer. If the measured substance is penetrable to radiant heat, the thermometer and the ambient wall surface exchange heat energy. This effect need not be considered for measured substances impenetrable to heat radiation. The following applies to a thermometer tube, the surface A of which has a different temperature from the ambient wall surface A_w and is small compared to A_w:

$$P_{st} = \alpha_{st} \cdot A \cdot (T_t - T_w) \qquad (2\text{-}56)$$

$$\alpha_{st} = a_{st} \cdot \varepsilon \cdot C_s$$

$$a_{st} = \frac{\left(\dfrac{T_t}{100}\right)^4 - \left(\dfrac{T_w}{100}\right)^4}{T_t - T_w}$$

$$C_s = 10^8 \cdot k = 5.67 \cdot \frac{W}{m^2 \cdot K^4}$$

P_{st}	= transferred thermal power
α_{st}	= heat radiation transfer coefficient
A	= thermocouple surface
a_{st}	= temperature factor
ε	= degree of emission of thermometer surface, see Table 2.11
C_s	= "Technical radiation constant" with k = Stefan-Boltzmann constant
T_t	= thermometer temperature
T_w	= surface temperature of vessel wall

Material	ε	$\varepsilon \cdot C_s$ [W/(m² · K⁴)]
Metals, alloyed steels polished	0.04 to 0.07	0.23 to 0.4
Aluminum sheet, raw	0.07	0.4
Iron sheet, nickel plated matte	0.55	0.65
Brass, matte	0.22	1.3
Iron sheet freshly lapped	0.25	1.4
Lead, nickel, oxidized	0.29	1.6
Steel sheet, rolling skin	0.65	3.7
Iron, copper oxidized	0.7 to 0.84	4 to 4.8
Ceramic materials, iron enameled	0.9 to 0.96	5.1 to 5.5

Table 2.11 Degrees of emission of different materials

These mechanisms are added together according to the superimposition law as total transferred thermal power. Hence the total transfer coefficient α_{th} is as follows:

$$\alpha_{th} = \alpha_k + \alpha_{st} \qquad (2\text{-}57)$$

In the real measuring situation a complex picture of the heat transfers and heat losses results. Figure 2.51 shows in simplified form a typical transfer chain of heat transfers as far as the sensor:

Figure 2.51   Heat resistance chain in the measuring process
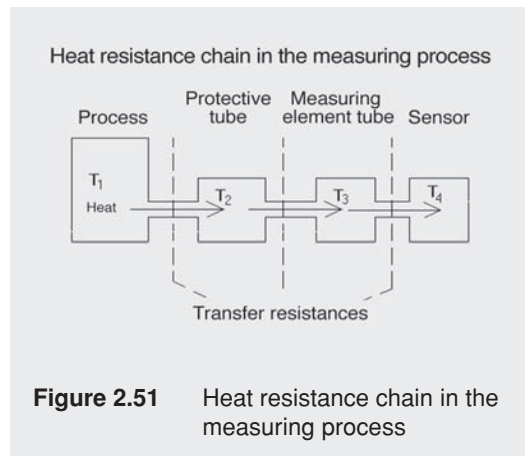
Linking and adding the heat conduction resistances and transfer resistances at a thermometer resembles the joining together and insertion of different pipes to form a pipe network. In the same way that the water flows through a pipe network to a pressure sensor, the heat energy must reach the sensor through the network of transfer resistances. If there is no heat loss as far as the sensor or at the sensor, the same temperature will prevail everywhere after a certain time despite the transfer resistances:

$$T_1 = T_2 = T_3 = T_4$$

applies.

Correspondingly the same pressure prevails everywhere in the case of water in a loss-free pipe network. This effect is used in pressure measurement. If a heat outflow exists at the sensor through which the heat energy is lost, a permanent temperature gradient is established between the tip of the thermometer and sensor according to the magnitude of the heat outflow:

$$T_1 > T_2 > T_3 > T_4$$

then applies.

Such a heat energy outflow always exists during the temperature measurement. In all immersion thermometers the heat flows via the thermometer tube to the environment. The heat energy may flow away via the flanged thermowell, the measuring element tube, the filling of the measuring element tube, the cable or the electrical connecting wires. All these heat loss possibilities should be taken into account. Figure 2.52 shows the possible heat flows.

A direct accurate calculation of the heat transfer error for a thermometer is very time-consuming and complicated. An equation system with at least ten differential equations dependent on each other has to be solved. Each possible connecting line between two temperature points must be described by a differential equation. If the heat transfer error of an individual thermometer in two different measured substances, i.e. water and air, is known, however, the behavior of this thermometer can be calculated via two thermometer-related **parameters K_T** and **V_T** for all other measuring conditions. The parameter K_T denotes the internal thermal conduction behavior of the thermometer. The parameter V_T is a measure of the entire heat transfer behavior of the thermometer regardless of the measured substance used. If measurement is carried out in a measured substance X other than water or air, the thermometer behavior is calculated with the aid of the conversion factors a_G for gases in relation to air and a_F for liquids in relation to water (see Table 2.10).
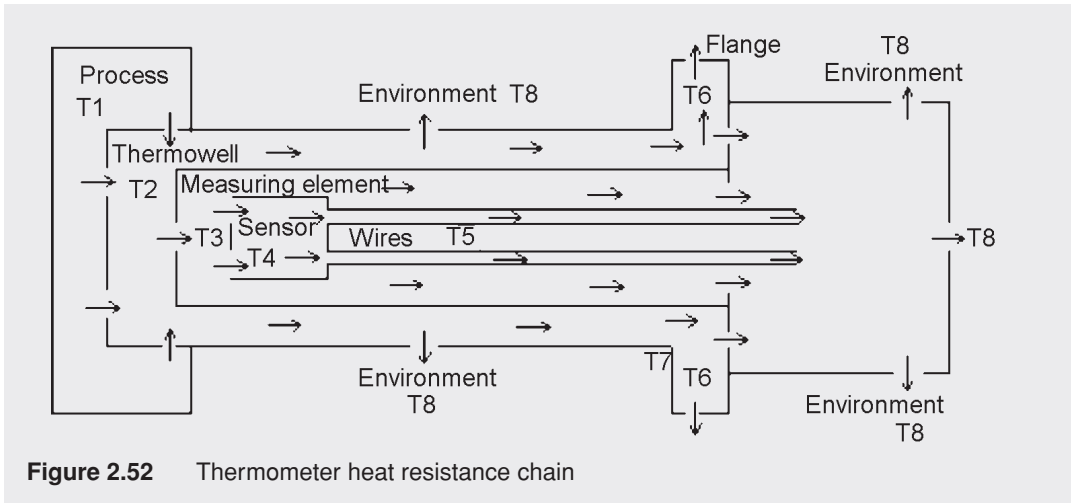
Figure 2.52   Thermometer heat resistance chain

Mathematically the **effective heat transfer coefficient** a_{eff} is represented as the sum of two coefficients:

$$\frac{1}{\alpha_{xeff}} = \frac{1}{\alpha_{thx}} + \frac{1}{c_{th}} \qquad (2\text{-}58)$$

α_{eff} = the effective transfer coefficient for the measured substance X

α_{thx} = the transfer coefficient α_{th} for the measured substance X according to equation 2-55

c_{th} = constant internal transfer coefficient for this thermometer, which is based only on the type of thermometer

As a second step, a hypothetical measured substance M is introduced. M has a transfer coefficient one hundred times that of the measured transfer coefficient in air for this thermometer, which was determined at 1 m/s.

$$\frac{\alpha_{thm}}{\alpha_{thL}} = 100 \qquad (2\text{-}59)$$

α_{thm} = transfer coefficient of the thermometer in the measured substance M

α_{thL} = transfer coefficient of the thermometer in air according (1 m/s)

The effective transfer coefficient in the hypothetical measured substance M in relation to the effective transfer coefficient in air is defined as thermometer parameter V_T.

$$V_T = \frac{\alpha_{meff}}{\alpha_{Leff}} \qquad (2\text{-}60)$$

V_T = thermometer parameter for the total transfer behavior

a_{meff} = effective transfer coefficient in measured substance M

a_{Leff} = effective transfer coefficient in air (1 m/s)

V_T is thus a parameter, which is determined only by the type of thermometer. The effective transfer coefficient for an optional measured substance X is then:

$$\frac{\alpha_{Leff}}{\alpha_{xeff}} = \frac{1}{0{,}99\,V_T} \cdot \left[\frac{V_T - 1}{\left(\frac{\alpha_{thx}}{\alpha_{thL}}\right)} + 1 - \frac{V_T}{100} \right]$$

$$(2\text{-}61)$$

If the standard measurement in water is inserted for measured substance, X, V_T can be determined from the standard measurements in air and water:

$$V_T = \frac{\frac{\alpha_{thw}}{\alpha_{thL}} - 1}{\left(\frac{\alpha_{thw}}{\alpha_{thL}}\right) \cdot \left(0.01 + 0.99\,\frac{\alpha_{Leff}}{\alpha_{weff}}\right) - 1}$$

$$(2\text{-}62)$$

Definition of K_T:
K_T contains the summary of the internal heat conduction constants λ_i with the structure geometry referred to the standard measurement in air.

For a thermometer, which has the sensor at its tip and a large length compared to the sensor length, the following applies to the static relative **installation error** F_x in the measured substance X:

$$F_x = \frac{1}{\cosh\left(\sqrt{\frac{\alpha_{xeff}}{\alpha_{Leff}} \cdot K_T}\right)} \qquad (2\text{-}63)$$

with

$F_x = \dfrac{T_x - T_{thx}}{T_x - T_w}$ = relative installation error in the measured substance X

T_x = temperature of the measured substance X

T_{thx} = sensor temperature in the measured substance X
= measured value of the thermometer in X

T_w = wall or flange temperature of the thermometer

K_T = thermometer parameter

The relationship between F_x and the term under the root in equation 2-63 is shown in Figure 2.53:

Figure 2.53 Relationship between $\dfrac{\alpha_{xeff}}{\alpha_{Leff}} \cdot K_T$ F_x and K_T
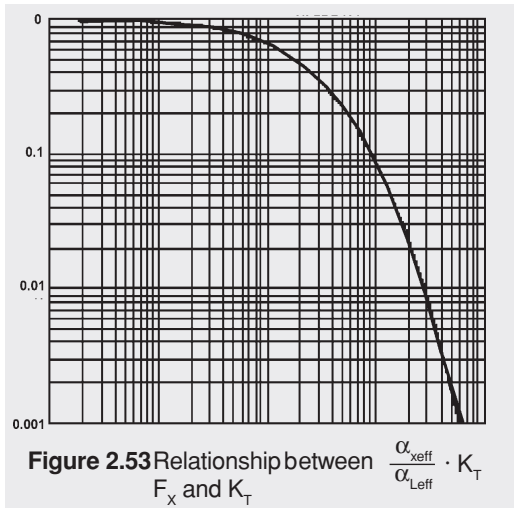
The following applies to the relative measurement error in air F_L under standard conditions:

$$F_x = \cfrac{1}{\cosh\left(\sqrt{\dfrac{\alpha_{xeff}}{\alpha_{Leff}} \cdot K_T}\right)} \qquad (2\text{-}64)$$

$$\frac{\alpha_{xeff}}{\alpha_{Leff}} \cdot K_T = K_T$$

$$K_T = \left(\text{acosh}\left(\frac{1}{F_L}\right)\right)^2$$

Therefore, K_T can be determined directly from the standard measurement in air.

The thermometer constants K_T and V_T can be determined in the following way:
a) Determination of α_{thw} and α_{thL} for the standard measurement with the aid of Figs. 2.47, 2.48, 2.49, Tables 2.8, 2.11 and the corresponding equations 2-53 to 2-57

b) Experimental determination of the relative error F_L with Figure 2.53 or equation 2-64.
c) Determine K_T from F_L with Figure 2.5.3 or equation 2-64. a is determined with Figure 2.53 and F_W, and

$$\frac{\alpha_{Leff}}{\alpha_{weff}} \cdot K_T$$

is calculated:

$$\frac{\alpha_{Leff}}{\alpha_{weff}} = \frac{K_T}{\dfrac{\alpha_{weff}}{\alpha_{Leff}} \cdot K_T}$$

V_T is then calculated with equation 2-62. Once V_T and K_T have been determined, the installation error for other measuring conditions and another measured substance X can easily be calculated.
d) α_{thx} and α_{thL} are determined from the tables and diagrams as under a). The root term of 2-64 is calculated with V_T and K_T from equation 2-61.

The relative installation error F_x is then determined with Figure 2.53.

2.4.2 Immersion depth of the thermometer

The discussions in Section 2.4.1 are based on the requirement that the thermometer penetrates so deeply into the different measured substances that the measuring conditions are comparable.
The **immersion depth** is the length of the thermometer that penetrates or immerses directly into the measured substance
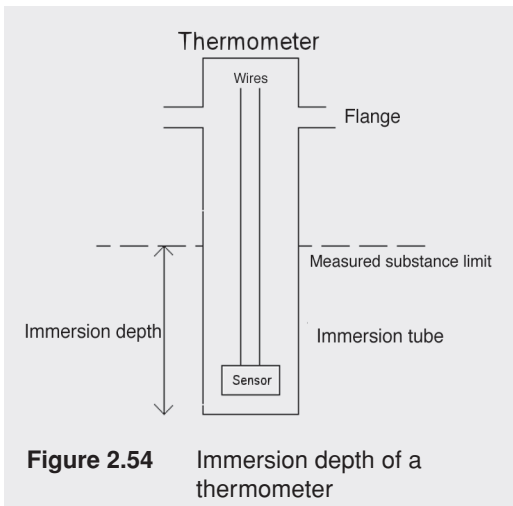
Figure 2.54 Immersion depth of a thermometer

The **active length** of a thermometer is the length over which the thermometer effectively averages the temperatures as a result of heat inflows and outflows. Therefore the **minimum immersion depth** of the thermometer in the measured substance is the immersion depth, below which the measurement lies within the required accuracy. An immersion depth of the active length plus 15 x di-

Figure 2.55 Graph of immersion depth measurement
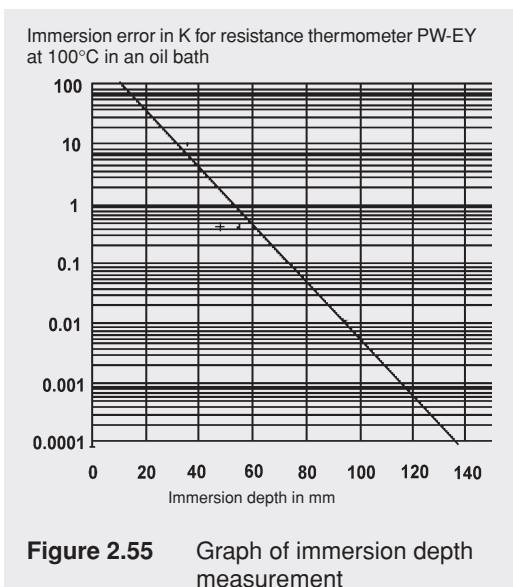
ameter of the thermometer should be used for standard measurements. The active length or minimum immersion depth is determined by gradual withdrawal from a temperature control bath (see Section 3.2.3.3). The measured value is determined for each immersion depth and the measuring error plotted over the immersion length.

2.4.3 Self-heating of electrical thermometers

If the temperature is measured with a resistance thermometer, the electrical resistance R_S of the sensor must be measured with the aid of a current I_m. The electrical output P_V is thus present as heat energy at the measuring resistance R_S:

$$P_V = R_S \cdot I_m{}^2 \qquad (2\text{-}65)$$

If $I_m = 1$ mA and $R_S = 300\ \Omega$, an output of $P_V = 0.3$ mW results.

In the thermometer there is therefore a heat source directly on the sensor, the heat energy of which adds the self-heating error to the measured value. This heat energy must be transferred away via the same heat couplings as those through which the heat energy flows inwards from the process or outwards to the thermometer root. For accurate temperature measurements the self-heating effect means that measurements should be made with the smallest possible currents and that the thermometer or sensor element has the best possible heat contact with the measured substance. So a measuring current I_m of maximum 1 mA is recommended for PT 100 resistance thermometers. With this order of magnitude of the measuring current the self-heating error generally remains below 0.05 K.

Very similar conditions to those for the static installation error apply to determining the self-heating error E_x.
The self-heating is measured in two different measured substances under normal conditions

(air and water according to Section 2.7.1.5) and a parameter V_{TE} determined on this basis for this thermometer. The self-heating error E_x in the measured substance X is calculated via this parameter V_{TE}. V_{TE} can be determined according to the following method.

a) Determination of a_{thw} and a_{thL} according to Section 2.4.1, equation 2-53 to 2-57.

b) Experimental determination of the self-heating error for a reference measuring current I_m in water and air according to Section 2.7.1.5.

c) The following equation applies:

$$\frac{\alpha_{Leff}}{\alpha_{weff}} = \frac{E_W}{E_L} \qquad (2\text{-}66)$$

E_W = self-heating error in water
E_L = self-heating error in air
α_{Leff} = effective transfer coefficient in air
α_{weff} = effective transfer coefficient in water

V_{TE} is calculated with equation 2-62.

The self-heating error E_x in the measured substance X can be calculated with known V_{TE}.

A requirement is that the same measuring current I_m as in the determination of V_{TE} is used. If the measurement is made with another measuring current I_{m2}, the determined self-heating error should be converted according to Section 2.7.1.5.

- According to Section 2.4.1 and 2.4.2 the heat transfer coefficient α_{thx} is determined for the measured substance X. Furthermore, α_{thL} from a) and E_L from b) are used.

- The following is calculated with equation 2-61 and V_{TE}:

$$\frac{\alpha_{Leff}}{\alpha_{xeff}}$$

- The self-heating error in measured substance X is then as follows according to equation 2-66:

$$E_X = \frac{\alpha_{Leff}}{\alpha_{xeff}} \cdot E_L \qquad (2\text{-}67)$$

2.5 Time response of direct contact thermometers

2.5.1 Time response in the water model

All physical transfer processes, be it water or heat transfer, are processes in time. The time was considered in Section 2.4. Only the temperature established as the equilibrium state after sufficient time was described in that section.

Until the equilibrium state is reached the time response of the heat energy can be compared with the behavior of water transfer. In this comparison the temperature measuring point is represented by a large water tank, the process with pressure P_0, and several smaller tanks with the volumes V_1 and V_2, which are connected to each other by pipes and filled in succession.
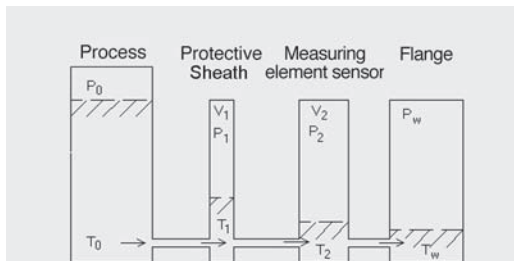
Figure 2.56 Equalizing flows of adjoining water tanks

The pressure $P_1 = P_2 = 0$ in the tanks at time t_0. Each tank must be filled completely until it can fully transfer the water pressure representing the temperature. The tank size represents the **heat capacity**. The water quantity, which can flow per second from one tank to the next, depends on the pressure differential between the tanks. The more equally the tanks are filled, the more slowly the pressure equalization takes place. The water quantity per second corresponds to the **thermal output** or **heat flow** between the tanks, and the pressure difference to the temperature difference.

2.5.2 RC models for description of the dynamic behavior of thermometers

2.5.2.1 Thermometer with exponential transient response and the RC model

The heat transfer behavior in relation to time follows a frequently observed pattern described in the literature – **R-C elements** (resistance/capacitor combinations) in electronic circuitry.
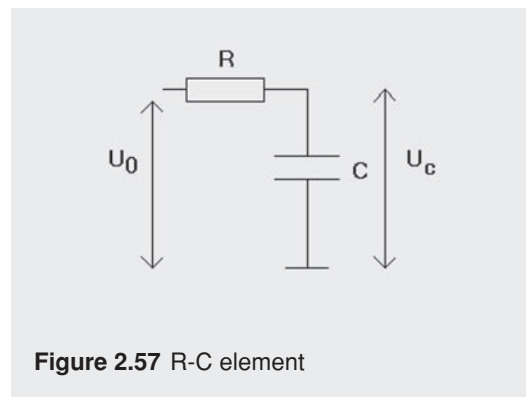
Figure 2.57 R-C element

In Figure 2.57:

electrical resistance R = heat transfer resistance $1/\alpha$

voltage U_0 = measured substance temperature T_m

voltage U_C = thermometer temperature T_{th}

electrical capacitance = heat capacity of the thermometer C_{th}

electrical current I = heat flow

The following applies to the time response of voltage U_c:

Dynamic relative response error:

$$\delta_c (t - t_0) = \frac{U_c(t) - U_c(t_0)}{U_c(t_0) - U_0} = e^{-\frac{t-t_0}{R \cdot C}} \qquad \text{(2-68)}$$

Relative transient response:

$$\eta_c (t - t_0) = \frac{U_c(t) - U_0}{U_c(t_0) - U_0} = e^{-\frac{t-t_0}{R \cdot C}}$$
$$= 1 + \delta_c (t - t_0) \qquad \text{(2-69)}$$

$U_c(t)$	=	voltage at capacitor at time t
U_0	=	constant process voltage at the R-C element input
t_0	=	starting time

The time $t = t_0 + \tau_c$, at which the voltage difference $U_0 - U_c(t)$ falls to a 1/e of the starting value, is

$$\tau_c = R \cdot C \qquad \text{(2-70)}$$

so that

$$\eta_c (t - t_0) = 1 - e^{-\frac{t-t_0}{\tau_c}} \qquad \delta_c (t - t_0) = 1 - e^{-\frac{t-t_0}{\tau_c}}$$

applies.

The time response of a thermometer with a uniform cross-section and construction over the active length (see Section 2.4.2) conforms physically to the time response of an R-C element. Therefore thermometers of this type are designated **thermometers with exponential transient response**.
According to the R-C element, the formulas for the **dynamic relative response error** apply. (For simplification $t_0 = 0$ is inserted).

$$\delta (t) = \frac{T_{th} (t) - T_{th} (0)}{T_{th} (0) - T_m} = e^{-\frac{1}{\tau}} \qquad \text{(2-71)}$$

transient response:

$$\eta (t) = \frac{T_{th} (t) - T_m}{T_{th} (0) - T_m} = 1 - e^{-\frac{1}{\tau}} = 1 + \delta(t) \qquad \text{(2-72)}$$

$T_{th}(t)$	=	thermometer temperature at time t
T_m	=	measured substance temperature

with:

$$\tau = \frac{V \rho c_{th}}{A \alpha_{xeff}} \qquad \text{(2-73)}$$

τ	=	time constant
V	=	thermometer volume
ρ	=	mean density of the thermometer
c_{th}	=	mean specific heat capacity
A	=	thermometer surface
α_{xeff}	=	effective heat transfer coefficient

The temperature curve as a function of time is shown graphically in Figure 2.58 for a thermometer with $\tau = 1$ s:
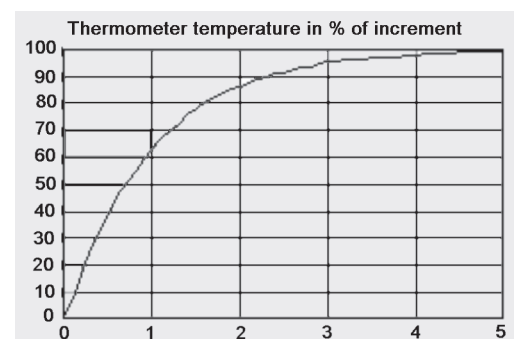
Figure 2.58 Time dynamic response of a thermometer with exponential transient response

In addition to the **time constant** τ the **t_{10} time** (10% of the error has decayed), the **half-period t_{50}** (50% of the error has decayed) and the **t_{90} time** (90% of the error has decayed) are important parameters in metrology. The following applies to a thermometer with **exponential transient response** (in factors of τ):

$$t_{10} = 0.104\tau \qquad\qquad \text{10\% time}$$

$$t_{50} = \tau \cdot \ln 2 = 0.693\tau \qquad \text{50\% time} \quad (2\text{-}74)$$

$$t_{90} = 2.303\tau \qquad\qquad \text{90\% time}$$

The ratio of t_{90}/t_{50} is:

$$\frac{t_{90}}{t_{50}} = 3.32 \qquad\qquad (2\text{-}75)$$

With measurement of the ratio t_{90}/t_{50} it can easily be checked whether a thermometer has an exponential transient response.

With exponential time dynamic response of the thermometer a straight line in a semi-logarithmic graph (Figure 2.59) represents the magnitude of the dynamic response error (t).
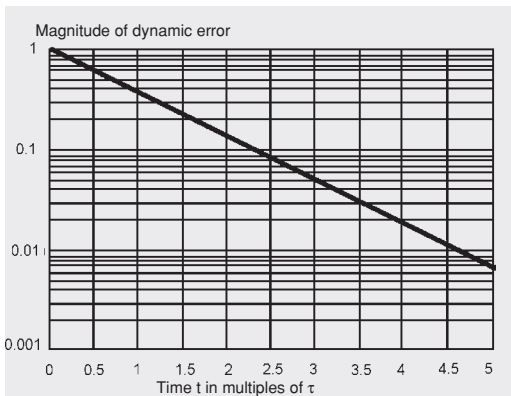
Figure 2.59 Dynamic response of an exponential thermometer

A thermometer with exponential transient response can be regarded as a simple delay element like an R-C element. The frequency response is described by:

$$F(p) = \frac{1}{1 + p \cdot \tau} \qquad p = i\omega \qquad (2\text{-}76)$$

$$
\begin{aligned}
f(p) \quad &= \quad \text{complex frequency response} \\
\omega \quad &= \quad \text{angular frequency (Hz)} \\
\psi\,(\omega) \quad &= \quad \text{arcan}\left(\frac{\omega}{\tau}\right) \\
\psi \quad &= \quad \text{Phase delay}
\end{aligned}
$$

The **limiting frequency** f_g, at which the thermometer reaction has fallen to about 70% of the time dynamic response in the measured substance, is:

$$f_g = \frac{1}{2\,\pi\,\tau} \qquad\qquad (2\text{-}77)$$

The limiting frequency f_g equals 0.16 Hz for a thermometer with $\tau = 1$ s.

This means that if the temperature in the measured substance increases by 10 K/s, the first recognizable temperature rise of this thermometer occurs about 1 s later and the indication is continuously about 10 K too low as long as the temperature rise persists. If the temperature rise in the measured substance ends, the measuring error of 10 K decays with the response times (t_{50}, t_{90}).

2.5.2.2 Basic circuit of R-C model in temperature measurement

The actual construction of thermometers is seldom identical. Between the measuring element and protective sheath there is an air gap, which has a delaying effect. The sensor of thermocouples is often welded directly in the thermometer tip to the tube. The real time response is thus significantly affected.

a) If t_{90}/t_{50} exceeds 3.32, reference is made to a thermometer with **lead** or **surface effect**, because with the same τ t_{50} is smaller than for a thermometer with exponential transient response. Thermometers with a sensor near the surface, i.e. in the case of a welded thermocouple, have a lead.

b) If t_{90}/t_{50} is equal to 3.32, the exponential transient response or volume effect applies.

c) If t_{90}/t_{50} is less than 3.32, reference is made to a thermometer with **lag** or **center effect**, because with the same τ t_{50} is greater than for a thermometer with exponential transient response. A lag occurs in thermometers whose sensor is located in the **tube center**, i.e. in PT 100 standard measuring elements. Lag likewise occurs in thermometers, which are installed with an air gap in the protective sheath. These thermometers exhibit an "S curve" as transient response.

Figure 2.60 shows the time curve of the transient response for the exponential case, lead and lag.
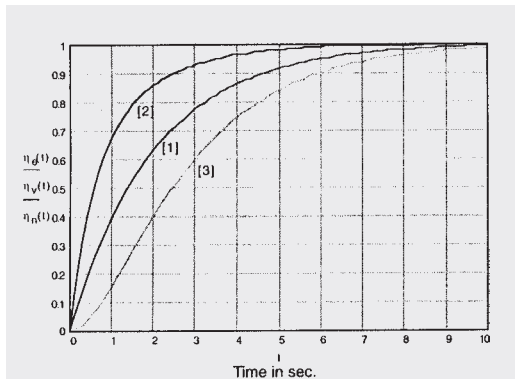
Figure 2.60 Transient responses of different thermometers with exponential curve [1], lead [2] and lag [3]

If the dynamic error functions of these types of thermometers are represented in semi-logarithmic form (Figure 2.61), characteristic deviations from a straight line are evident in thermometers with lead or lag.
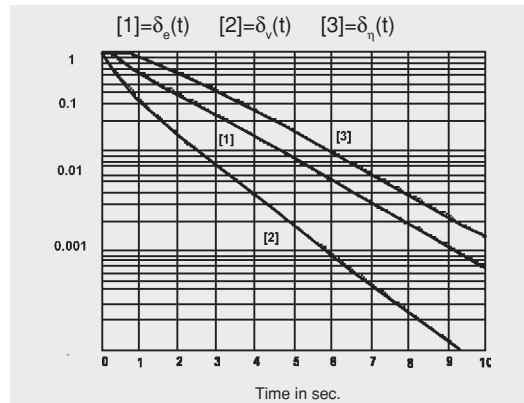
Figure 2.61 Dynamic error of different thermometers with exponential curve [1], lead [2] and lag [3]

The time response of the thermometer determined by the type of construction can be represented symbolically by the combination of several R-C elements. A system with lag can be represented i.e. by connection of two R-C elements in series.
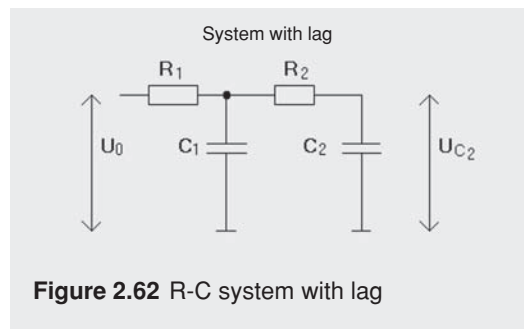
Figure 2.62 R-C system with lag

The transient response can generally be represented as the superimposition of several exponential functions. Two exponential functions are usually adequate for sufficiently accurate representation. The mathematical representation of the transient response h and the complex frequency response F(p) is as follows for this case:

$$\eta_{th}(t) = 1 - \frac{\tau_1 - \tau_v}{\tau_1 - \tau_2} \cdot e^{-\frac{1}{\tau_1}} + \frac{\tau_2 - \tau_v}{\tau_1 - \tau_2} \cdot e^{-\frac{1}{\tau_2}}$$

(2-78)

and

$$F(p) = \frac{1 + p + \tau_v}{(1 + p + \tau_1) \cdot (1 + p + \tau_2)}$$

(2-79)

τ_v = lead time constant
τ_1, τ_2 = delay time constant

2.5.3 Characteristic values for the time response

The **characteristic values t_{50}, t_{90}** are used for comparison of the time response of different thermometers. t_{50} means that the sensor "perceives" only its near environment in the measured substance and thermometer. t_{90} means that the sensor additionally "perceives" the effect of the more **distant** parts of the thermometers. This behavior allows thermometers to be manufactured selectively according to the required time response. The position of the sensor, suitable selection of the materials and the geometrical design can adjust the required damping behavior.

The actual characteristic values t_{50}, t_{90} of the thermometer are specific to the measured substances and are significantly affected by the measuring conditions just like the static heating error (Section 2.4). Since accurate calculation via the thermometer construction is extremely difficult, measurement of the thermometer transfer times for two standardized measuring conditions for the required value of η and formation of a constant V_{Th} on this basis is also used as methods in this case. With V_{Th} and the measured transfer times t_w and t_L, the transfer time t_x in the measured substance X can then again be determined for this value of η when the heat transfer coefficients for the measured substance X (α_{thx}) and for air (α_{thL}) are known.

a) Determination of V_T
- α_{thw} and α_{thL} are determined according to standard measurement practice with the aid of Figures 2.47, 2.48. 2.49 and Tables 2.8, 2.11 and the corresponding equations 2-53 to 2-57.

- t_w and t_L are determined experimentally for the required transient value (e.g. t_{50}, t_{90}) in water and air.

- The following applies:

$$\frac{t_w}{t_L} = \frac{\alpha_{Leff}}{\alpha_{weff}}$$

(2-80)

α_{Leff} = effective transfer coefficient in air
α_{weff} = effective transfer coefficient in water
t_w, t_L = transfer time in water and air with fixed η

V_{Th} is then calculated with equation 2-62.

b) Determination of the transfer time t_x for η in measured substance X
- According to Sections 2.4.1 and 2.4.2 the heat transfer coefficient a_{thx} is determined for measured substance X. Further, a_{thL} and t_L from a) are used.

- The following is calculated with equation 2-61 and V_{Th}:

$$\frac{\alpha_{Leff}}{\alpha_{xeff}}$$

- The transfer time t_x sought for η in measured substance X is then:

$$t_x = t_L \cdot \frac{\alpha_{Leff}}{\alpha_{xeff}}$$

(2-81)

Temperature measuring instruments, mechanical bi-metal system, gas pressure systems and thermowells

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2.6 Industrial expansion thermometers

Expansion thermometers are industrial temperature measuring instruments in which the input quantity "temperature" is indicated as a function of the expansion behavior of temperature-dependent materials. When the expansion is contained, the change in other physical state variables (pressure) is used for temperature indication.

2.6.1 Glass thermometers

Glass thermometers are a widely used type of expansion thermometer. They operate in temperature ranges from -330°F to 2200°F (-200°C to 1200°C).

Good adaptability to different measuring conditions, high measuring accuracy, and simple construction make these thermometers economical. The **operating principle of glass thermometers** is based on the thermal expansion of a thermometric liquid in a closed glass bulb (thermometer bulb). The temperature is directly indicated by the level of the liquid in a stem (capillary) connected to the thermometer bulb. The height of the column in the stem is a function of the difference between the thermal expansion of the glass bulb and the dependence of the thermometric liquid on the temperature being measured.

The sensitivity of glass thermometers depends on the volume of the thermometer bulb, the inside diameter of the stem and the properties of the thermometric liquid. Improvements in the sensitivity are made, for example, by increasing the bulb volume, reducing the stem cross-section and printing scale graduations. However, these measures must always be selected in consideration of the specific technical application. For example, there narrow tolerances for reducing the stem cross-section because of the forces acting on the liquid, and a larger bulb volume gives the thermometer a greater inertia.

Construction and types

The two most common types of glass thermometers are etched glass and industrial glass (Figure 2.63).

A) Etched glass thermometer
1   Main scale
2   Liquid filling
3   Thermometer bulb
4   Expansion chamber
5   Capillary tube
6   Contraction chamber

B) Industrial glass thermometer
1   Main scale
2   Liquid filling
3   Thermometer bulb
4   Expansion chamber
7   Connecting capillary
8   Stem
9   Sheathing tube
10 Thermometer closure
11 Division mark
12 Upper portion
13 Lower portion
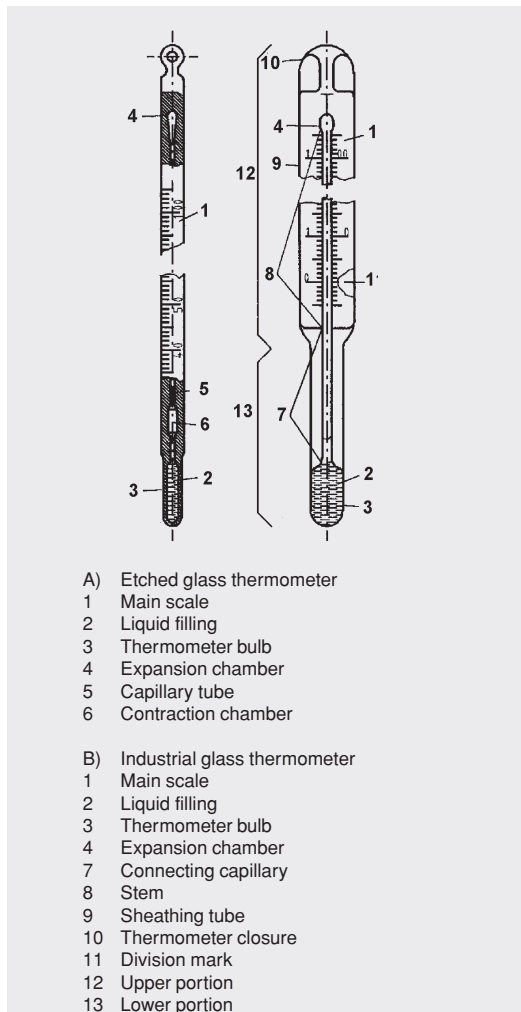
Figure 2.63 Basic types of glass thermometers

On an **etched glass thermometer** the scale is imprinted or etched onto the front of the thick-walled stem.

On the **industrial glass thermometer**, on the other hand, the stem is attached to a strip on which a graduated scale is printed. Both the stem and the printed strip are enclosed by a gastight sheathing tube. The scale strip is held securely against the stem in such a way that the scale end can expand freely when heated.

The **main scale** of a glass thermometer has the graduations required for the corresponding temperature range. Some thermometer types have an **auxiliary scale** for checking the thermometer and possibly a mark for the lower temperature range limit.

The internal cross-section of the **stem** is smooth and must not deviate by more than 2% from the mean value at any point. The stem cross-sections are round, oval, flattened on one side or frequently designed as cylindrical lenses for column magnification in mercury thermometers. Glass thermometers can be supplied with a **contraction chamber** in the lower part of the stem which allows suppression of the temperature indication in a specific temperature range.

An **expansion chamber** at end of the stem prevents damage to the thermometer in the event the temperature range is exceeded.

The **immersion depth** is the specified length which must be immersed in the measured substance in order to supply correct measured values within the specified measuring accuracy.

Total immersion thermometers are exposed to the temperature being measured only as far as the column tip.

Partial immersion thermometers are exposed to the temperature up to a pre-determined immersion line which is marked on the thermometer stem, and an associated column reference temperature. If thermometers are **fully immersed** in the measured media, the end of the stem including the expansion chamber are below the surface of the media during measurement. The thermometric liquid of a glass thermometer depends on the measurement requirements such as temperature range, required sensitivity, time response and long-time stability.

A difference is noted between wetting (organic) and non-wetting (metallic) **thermometric liquids**. These liquids must have good volumetric stability over the full temperature range, and be free of gas and vapor bubbles.

The measuring uncertainty when using a wetting thermometer liquid is about one power of ten higher than for thermometers operating with a non-wetting liquid.

As a non-wetting thermometric liquid, mercury can be used in the temperature range from -37°F to about 1200°F (-38.5°C to 630°C) or up to about 1500°F (800°C) with quartz glass.

Mercury thermometers are filled with inert gas such as nitrogen or argon at temperatures over 400°F (200°C). As a result distilling or boiling of the thermometric liquid is suppressed in this temperature range. The required filling pressures are between 15 PSI (up to 650°F) and 1000 PSI (1400°F). At higher measuring temperatures, mercury-thallium alloys or gallium are used. The solidification points of non-wetting thermometric liquids (mercury -37°F and mercury-thallium -72°F) limit their use for lower temperature ranges. Therefore only glass thermometers with wetting thermometric liquids can be used for temperature ranges below -72°F to about -330°F. Typical thermometric liquids and their temperature ranges are shown in Table 2.12.

Non-wetting	Temperature range		
Mercury	-37.3	to	1166°F
(quartz glass)		to	1472°F
Mercury-thallium	-72.4	to	1832°F
Gallium	85.6	to	3740°F
Wetting			
Alcohol	-166	to	410°F
Toluene	-130	to	212°F
Pentane*)	-328	to	-8°F

*)-Mixture of normal pentane and isopentane

Table 2.12 Thermometric liquids for glass thermometers

Glass thermometers are made of glass with a high chemical resistance and small thermal after-effect. Some examples of common **thermometer glasses** and their maximum operating temperatures are given in Table 2.13.

Designation	Manufacturer	Marking	Temperature (max.)
Standard glass N16	Schott & Gen.	red stripe	up to 750°F
Thermometer glass 2954	Schott & Gen.	black stripe	up to 850°F
Supremax	Schott & Gen.		up to 1100°F
Quartz glass			up to 2000°F

Table 2.13 Common thermometer glasses

Because of the rigidity of glass, the final application has to be considered. This has led to many diverse types of construction. Some important thermometer types will be briefly described below. **Stick thermometers** have an enclosed-scale. A long capillary connects the thermometer bulb and stem. The glass cylinder is tapered below the start of the scale so that the thermometer can be installed in a hole at the required immersion depth.

Angle thermometers have a bend in the stem area. Typical angles between the upper and lower parts of the thermometer are 90° and 135°.
Machine glass thermometers are used for monitoring temperatures of liquids, gases and vapors in pipes and vessels. They have a straight or angled connection stem that is immersed into the measured media. The thermometer stem is usually contained with the scale strip inside V-shaped housing. Machine glass thermometers are typically found in the process industry.

Figure 2.64 Machine glass thermometer

Pocket glass thermometers are contained in a protective housing or provided with a holder. They are used for general-purpose applications such as measuring room temperature.

Extremely small temperature differences or changes can be measured in temperature ranges from -4°F to 300°F with **adjustable thermometers** (Beckmann thermometers). The main scale of the enclosed-scale thermometer usually designed as a stick thermometer has, for example, a temperature difference range of 5 K with a scale division of 0.02°F. The realistic measuring uncertainties are in the mK range. An adjusting device, which can be used to adjust the quantity of mercury required for the respective measurement and thus the zero point of this thermometer, is fused onto the upper end of the measuring capillary.

With their long thermometer bulb, **column thermometers** allow the determination of the mean temperature along a temperature gradient and are used for determining the column correction. These thermometers can be designed as enclosed-scale or stem thermometers.

Minimum/Maximum thermometers are specially designed to allow indication and storage of the minimum, maximum or both temperature values occurring within a selected period.

In **maximum thermometers** this is done by narrowing the stem above the thermometer bulb. It prevents the mercury from automatically falling back into the bulb after the maximum value is reached. Shaking the thermometer restores the initial condition. The best-known form of maximum thermometers is the **clinical thermometers**. Its has a range from 95°F to 108°F. The typical scale graduation is 0.2°F. The scale value 98.6°F is distinctly marked. Clinical thermometers may be sold only after official calibration.

Minimum thermometers operate with wetting thermometric liquids. Alcohol is often used. The liquid meniscus moves small metal markers when the temperature falls and remains at the lower temperature value. Inclining the thermometer can restore the initial condition.

James Six invented the principle of the minimum-maximum thermometer in 1782. The lower part of a U-tube is filled with mercury. An alcohol-based liquid is above the mercury in the two legs. One capillary leg is also constructed with an expansion chamber. Metal markers are located on the column tips of the mercury column and are displaced accordingly in the event of temperature changes. They are held by friction or magnetically when the mercury column returns. The maximum or minimum temperature can then be read off the oppositely directed scales.

Contact thermometers can be used directly in temperature control systems. They have permanently-fixed or adjustable electrical contacts built into the stem.

Parameters, errors and measuring uncertainties

The wetting properties of the thermometric liquids used affect the time response and reading of a thermometer.
The formation of a stable meniscus layer is impeded by the capillary depression which occurs with non-wetting thermometric liquids. The meniscus can be brought into its equilibrium state by lightly tapping the thermometer before the reading is taken.
Non-wetting thermometric liquids have a higher viscosity at low temperatures. The lag of the thermometric liquid on the capillary wall leads to delays. This situation can be avoided by approaching the measured temperatures from low to high temperatures.
The unavoidable vibrations that occur when handling the liquid thermometers may lead to **column separation** in the capillary, which should be eliminated before the start of measurement. The thermometric liquid can be rejoined in the expansion or contraction chambers by carefully cooling or heating the thermometer. In mercury thermometers this can also be accomplished by tilting or shaking the thermometer.

The **column error** and its correction are particularly important in more accurate measurements. It occurs in the event of deviation from the rated conditions under which the thermometer was adjusted during practical measurement. Column correction is necessary if:
- part of the column projects from the medium to be measured with a fully immersing, adjusted thermometer,
- the specific immersion depth is not heeded with a partially immersing adjusted thermometer,
- or the mean temperature of the projecting column deviates from the specified column reference temperature.

The column correction k_f can then be determined as follows:

$$k_f = \gamma \cdot \frac{1}{E} \ (t_{fs} - t_f) \qquad (2\text{-}82)$$

γ	=	relative coefficient of expansion of the thermometric liquid in relation to the thermometer glass
l	=	length of the column section for which the column temperature t_f is different from the column temperature t_{fs} prevailing under rated conditions
E	=	sensitivity of the thermometer
t_{fs}	=	specified column temperature
t_f	=	column temperature

If the column section deviating from the specified column temperature falls in the range of the thermometer scale, the ratio l/E is equal to the difference of the temperatures corresponding to the ends of the column section $(t_o - t_u)$.

This temperature difference is often specified by the number of scale divisions corresponding to the column section.
It is adequate to assume the following values for γ for most measurements in industrial laboratories and plants:

Mercury/mercury-thallium	$1.6 \cdot 10^{-4} \text{K}^{-1}$
Gallium	$1.0 \cdot 10^{-4} \text{K}^{-1}$
Pentane	$1.0 \cdot 10^{-4} \text{K}^{-1}$

The corrected temperature value is obtained in these cases by the addition of the calculated column correction k_f to the temperature read off the main thermometer.
In highly accurate measurements the dependence of the coefficient of expansion on the type of thermometer glass used and on the temperature should be considered.
A column thermometer arranged as close as possible to the main thermometer is used to measure the column temperature. The lower end of this auxiliary thermometer must be immersed about one-half inch into the measured medium. Its upper bulb end should be roughly at the height of the temperature to be read.

Thermal effects of the thermometer glass affect the stability of the reading of a glass thermometer. They can lead to an increase or decrease of the thermometer reading as a consequence of a change in the volume of the glass.
A reduction in the volume of the glass after manufacture of the thermometer leads to an **increase** in the indication. This effect is greatly reduced by use of especially suitable thermometer glasses and thermal stabilization processes during production. Calibratable thermometers with a full scale value over 400°F are checked for thermal stability by determining the deviation of the indi-

cation at a low reference temperature after heating for 24 hours to the full scale value.

At the freezing point the rated calibration error limits for the thermometer may not be exceeded or, alternatively, a change in reading no larger than 0.3 times the interval between scale divisions can be accepted. In the case of temperature changes, the bulb volume adjusts itself to the new equilibrium state only after a time lag. In particular during rapid cooling from a high temperature above 212°F, **depression** causing a reduction of the thermometer reading may be encountered. If the deviation of the thermometer is determined at a low temperature corresponding to the freezing point (32°F), freezing point depressions between 0.01 K and 0.05K can be detected for good thermometers. If the temperature changes are not too high, the depression is reversible and is reduced after a few days. To check the effect of depression on the freezing point correction, accurate thermometers have an auxiliary scale for the freezing point.

The volume of the thermometer bulb is influenced by the **internal and external pressure**. For example, the horizontal installation position of a vertically adjusted thermometer, installation in a vessel under pressure or immersion of a thermometer filled with protective gas beyond the extension for expansion all affect the indication. The internal pressure coefficient should be assumed to be about 0.1 K/bar. The external pressure effect is generally about 10% lower.

The maximum error limits glass thermometers are specified in Tables 2.14 and 2.15.

Temperature range [°F]		Scale value [°F]			
from	to	0.5	1	2	5
-330	-165		5.4	7.2	9
-165	15	1.8	3.6	7.2	9
15	230	1.8	3.6	5.4	9
230	410		5.4	7.2	9

Table 2.14 Error limits in °F for fully immersing, adjusted thermometers with wetting liquid

Temperature range [°F]		Scale value [°F]								
from	to	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5
-70	15				0.54	0.72	0.90	1.8	3.6	9
15	230	0.07	0.11	0.18	0.36	0.54	0.9	1.8	3.6	9
230	410					0.72	0.9	1.8	3.6	9
410	770						1.8	3.6	3.6	9
770	1130							5.4	7.2	9
above 1130									18	18

Table 2.15 Error limits in °F for fully immersing adjusted thermometers with non-wetting thermometric liquid

The obtainable measuring uncertainties with glass thermometers are substantially smaller than the specified error limits. A summary of the measuring uncertainty remaining after considering all error sources for fully immersing adjusted thermometers is given in Tables 2.16 and 2.17.

Temperature range [°F]		Scale value [°F]					
from	to	0.2	0.5	1.0	2	5	10
-330	-75	1.8	1.8	1.8	1.8	3.6	5.4
-75	15	0.54	0.54	0.9	1.8	3.6	5.4
15	230	0.54	0.54	0.9	1.8	3.6	5.4
230	410		0.9	0.9	1.8	3.6	5.4

Table 2.16 Absolute amounts of the measuring uncertainties for glass thermometers with wetting thermometric liquid

Temperature range [°F]		Scale value [°F]									
from	to	0.01	0.02	0.05	0.1	0.2	0.5	1.0	2.0	5	10
-72	-14		0.04	0.06	0.06	0.10	0.2	0.4	0.9	1.8	5.4
-14	230	0.02	0.04	0.06	0.06	0.10	0.2	0.4	0.9	1.8	5.4
230	410		0.04	0.10	0.10	0.2	0.4	0.6	0.9	1.8	5.4
410	590				0.2	0.4	0.4	0.6	0.9	1.8	5.4
590	950					0.9	0.9	0.9	1.8	0.4	5.4
950	1150						1.8	1.8	1.8	1.8	5.4
1150	1500							3.6	3.6	5.4	9
1500	1800							18	18	18	

Table 2.17 Absolute amounts of the measuring uncertainties for glass thermometers with non-wetting thermometric liquid

2.6.2 Dial thermometers

Dial thermometers are mechanical temperature measuring instruments with scaled dial and pointer. Bimetal thermometers, spring thermometers with a flexible measuring element and, in a broader sense, stem-type expansion thermometers are classified in this group.
Bimetal thermometers have a specially designed thermostatic bimetal element consisting of two metal strips that are bonded together. Each of the strips has a different thermal expansion characteristic that causes the strip to change its curvature as the temperature changes.
In spring thermometers the relative thermal expansion of a liquid or gas in a closed metal bulb is used for measurement. Depending on the type of bulb fitting, a distinction is made between liquid, vapor pressure and gas pressure spring thermometers. In these thermometers the thermometer vessel (metal vessel), capillary and flexible measuring element (tube spring) always form a self-contained unit. A pointer is then driven by a movement.

2.6.2.1 Stem-type expansion thermometer

If the ends of two stems are connected that are made of materials with different thermal expansion coefficients, the temperature-dependent difference in length of the two free ends can be used for temperature measurement. Figure 2.65 shows a schematic representation of a stem-type thermometer.
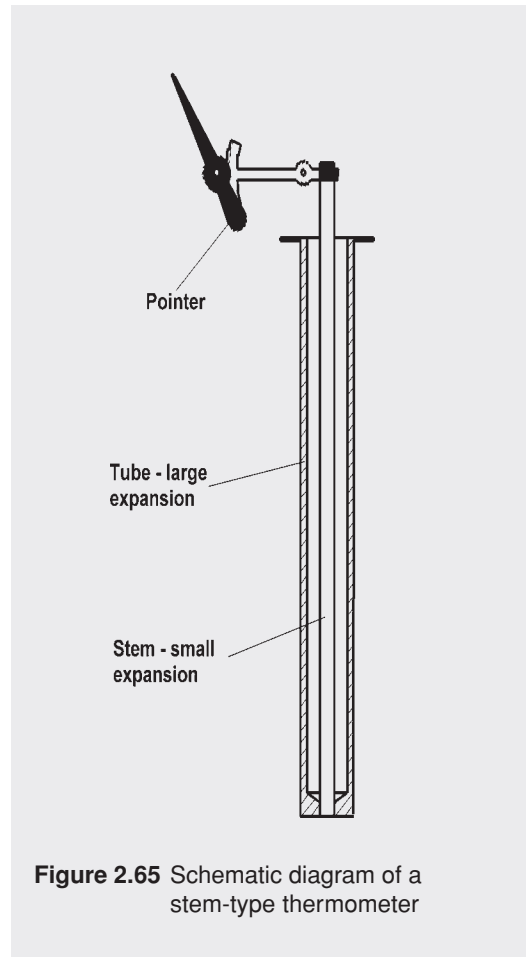
Figure 2.65 Schematic diagram of a stem-type thermometer

Quartz, porcelain or invar, for example, are used as materials with a small thermal expansion co-efficient. These are generally inserted in stem form into thin-walled metal tubes closed at the bottom and securely connected to these tubes. Depending on the temperature range these tubes can be made of brass ($\leq$ 600°F), nickel ($\leq$ 1100°F) or also stainless steel (up to 1800°F) (Figure 2.66).
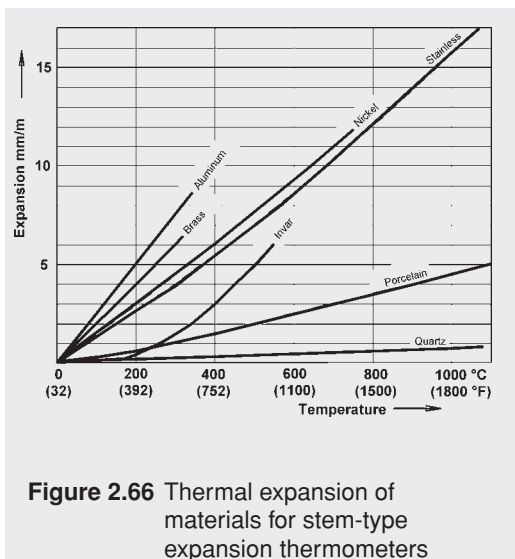
Figure 2.66 Thermal expansion of materials for stem-type expansion thermometers

Stem-type expansion controller
1 Deflection limiter
2 Contact
3 Inner stem with small expansion coefficient
4 Enclosing tube with large expansion coefficient
5 Adjustment scale
6 Pointer
7 Transmission elements

Figure 2.67 Stem-type expansion controller

The temperature-dependent difference in length of the stems is small and therefore requires long sensor lengths ($\geq$11 in.). In addition, transmission element are usually needed so that the temperature can be indicated with adequate pointer deflection. The effect of the transmission elements may lead to measuring errors amounting to 2% of the measuring span.

The large adjusting forces and rapid response sensitivity of the stem thermometers permits their direct use as a control element in simple control processes. The thermometers are often equipped with electrical switching contacts or connected to pneumatic or hydraulic controllers (Figure 2.67).

In other applications the thermal material expansion is used only as a sensor effect. Signal conversion into an electrical signal appropriate for remote transmission can then be made, i.e. by displaceable capacitor plates. Figure 2.68 shows a measuring set-up for temperature measurement by change in capacitance. In this case the expansion behavior of the duralumin wire controls the distance between two capacitor plates. The temperature-dependent change in capacitance is converted by an oscillating circuit into a frequency, which can be transmitted over long distances with high signal-to-noise ratio and, if necessary, by wireless mode. The measuring set-up described is used, for example, in radio-probes.
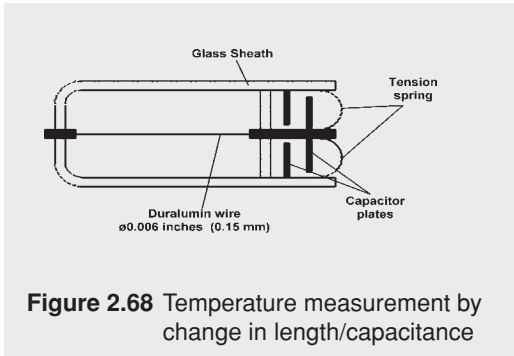
Figure 2.68 Temperature measurement by change in length/capacitance

2.6.2.2 Bimetallic thermometers

Construction and basic types

The temperature-sensitive **sensor element** of a bimetallic thermometer is a bimetallic strip designed as a spiral or helical spring. A temperature change is converted into a change in the angle of rotation by the bimetallic spring that is securely clamped at one end.
The simplest **thermometer types** consist of a **spiral spring** with a pointer shaft having a pointer mounted on its end. The measured temperature can be read off the graduated thermometer dial (Figure 2.69).
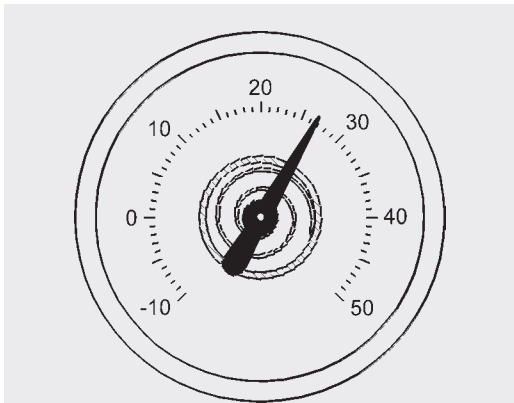
Figure 2.69 Bimetallic thermometer with bimetallic spiral

When the measuring and indicating sections are physically separated, the **helical spring** is housed in a long stem. The temperature-dependent rotation is transmitted via a shaft to the pointer located in a housing section at the top end of the stem (Figure 2.70). If the pointer shaft is in a radial position in relation to the thermometer housing, the rotational movement is transmitted to the pointer with low friction by a deflector spring or angular movement.

1 Pointer
2 Dial with scale
3 Bimetal strip
4 Stem
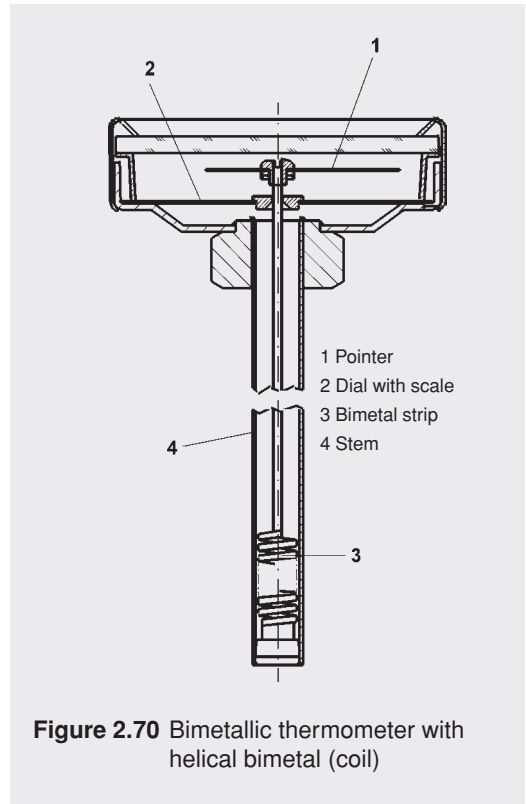
Figure 2.70 Bimetallic thermometer with helical bimetal (coil)

The **temperature range** of bimetallic thermometers is between −100°F and 1000°F (-70°C and +550°C). The preferred range of application extends from −60°F to about 750°F (-50°C to 400°C). Composites, called **thermostatic bimetals**, are used as basic materials for the spirals or helical springs. They consist of two metal

layers (components) of roughly the same thickness but with different thermal expansion characteristics permanently welded to each other. The material components are selected to have the greatest possible difference between the thermal expansion coefficients.

The component with the higher coefficient of thermal expansion, which typically exceeds $15 \cdot 10^{-6} K^{-1}$, is often designated the **"active" component** of the bimetal. It generally consists of an alloy, which contains iron, nickel, manganese or chromium in various compositions.

An iron-nickel alloy with 36% nickel (invar) is often used as the **"passive" component** with a smaller coefficient of expansion, typically below $5 \cdot 10^{-6} K^{-1}$. This material has a very small coefficient of expansion of $1.2 \cdot 10^{-6} K^{-1}$ at room temperature. Under the effect of temperature the bimetallic strip curves towards the component with the smaller coefficient of thermal expansion, i.e. towards the passive side.
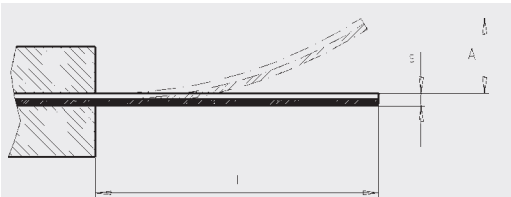
Figure 2.71 Thermal bending of a bi-metallic strip clamped at one end

Design of bimetals

A detailed knowledge of the temperature behavior of thermostatic bimetals is needed for the design and dimensioning of thermometers. Therefore the most important characteristic values and calculation principles will be examined.

The **free bending** of a bimetallic strip clamped at one end as a function of a change in temperature $(t_2 - t_1)$ can be described as follows (see Figure 2.71).

$$A = \frac{a \cdot l^2}{s} (t_2 - t_1) \qquad (2\text{-}83)$$

A = bending
a = specific thermal bending
l = strip length
s = strip thickness

The **specific thermal bending** of a bimetal is a temperature-dependent value determined by the different coefficients of expansion of the two materials used.

The partial suppression of the bending of the free bimetal end by transmission elements to an indicator requires an **adjusting force F**.

$$A = \frac{E \cdot s^3 \cdot b}{4 \cdot l^3} A_u \qquad (2\text{-}84)$$

A_u = partially suppressed bending
b = width
E = modulus of elasticity

If the bending is fully suppressed, a force F_U must be applied.

$$F_u = \frac{E \cdot a \cdot s^2 \cdot b}{4 \cdot l} (t_2 - t_1) \qquad (2\text{-}85)$$

The **work** performed in this case is dependent on the volume of the bimetal and thus not directly on the specific dimensioning of the strip thickness, width and length ($V = s \cdot b \cdot l$).

$$W = F_u \cdot A = \frac{E \cdot a^2 \cdot V}{4} \ (t_2 - t_1)^2 \qquad (2\text{-}86)$$

Spirals and helical springs made of thermostatic bimetals produce large deflections that can be used to indicate small temperature changes, and have small space requirements (Figure 2.72). The angle of rotation and the torque is important for their calculation.
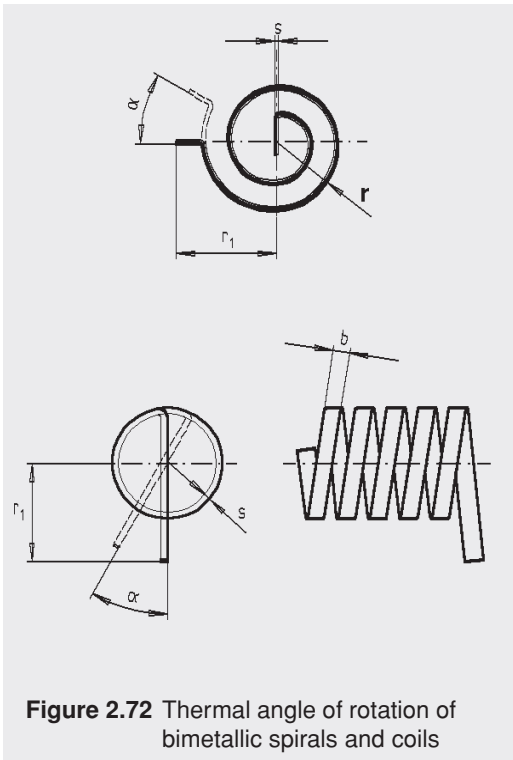
Figure 2.72 Thermal angle of rotation of bimetallic spirals and coils

The **angle of rotation** of a bimetallic spiral varies as a function of a temperature change according to the relationship:

$$\alpha = \frac{360°}{\pi} \cdot \frac{a \cdot l}{s} \ (t_2 - t_1) \qquad (2\text{-}87)$$

The free spiral end then covers the **path** A_r in the distance r_1.

$$A_r = \frac{2 \cdot r_1 \cdot a \cdot l}{s} \ (t_2 - t_1) \qquad (2\text{-}88)$$

The resulting **torque** also depends on the width and the modulus of elasticity E of the bimetal winding.

$$M = \alpha \cdot \frac{2\pi}{360°} \cdot \frac{E \cdot s^3 \cdot b}{12 \cdot l} \qquad (2\text{-}89)$$

For different bimetals the modulus of elasticity has values between 130 kN/mm² and 200 kN/mm² at room temperature (20°C).
With fully suppressed rotary motion the torque is given by the following:

$$M_u = \frac{E \cdot a \cdot s^2 \cdot b}{6} \ (t_2 - t_1) \qquad (2\text{-}90)$$

The **force** at the free spiral end M/r_1 is:

$$F = \alpha \cdot \frac{2\pi}{360°} \cdot \frac{E \cdot s^3 \cdot b}{12 \cdot l \cdot r_1} \qquad (2\text{-}91)$$

With fully suppressed bending and use of equation 2-89 for α, the following is obtained for the force:

$$F_u = \frac{s^2 \cdot b \cdot E \cdot a \cdot (t_2 - t_1)}{6 \cdot r_1} \qquad (2\text{-}92)$$

The **maximum allowable force** at which the bimetallic coil operates without permanent deformation is given by the equation:

$$F_{zul} = \frac{\sigma_{zul} \cdot s^2 \cdot b}{6 \cdot r_1}$$

(2-93)

The **working capacity** for spirals and coils is at its highest when the temperature change is utilized equally for path and force. If the volume V is inserted for the individual dimensions (s, b, l), the relationship for the work capacity is obtained.

$$W_{max} = \frac{A}{2} \cdot \frac{F_u}{2} = \frac{V \cdot a^2 \cdot E \cdot (t_2 - t_1)}{12}$$

(2-94)

The calculation principles specified provide guide values for the dimensioning of bimetals. The final values often have to be determined by detailed practical investigations.

If the **reading stability** of bimetallic thermometers has to meet stringent requirements, the reaction of the transmission elements can only be very small.

If **large bending** is required, bimetallic strips as thin as possible will be selected for indicating instruments.

Thermometers with additional equipment for the actuation of relays or switching contacts are equipped with suitably dimensioned bimetallic spirals with high adjusting forces.

If the **temperature indication is limited** by stops, permanent deformation of the spring must not occur when temperature ranges are exceeded.

The **linearity** between bending and temperature indication does not exist over the full temperature range because of the temperature dependence of the thermal expansion coefficients of the specific bimetallic components. However, bimetals may be used for temperature measurements over the linearity range from ±5% of the bending to their application limit (Figure 2.73).
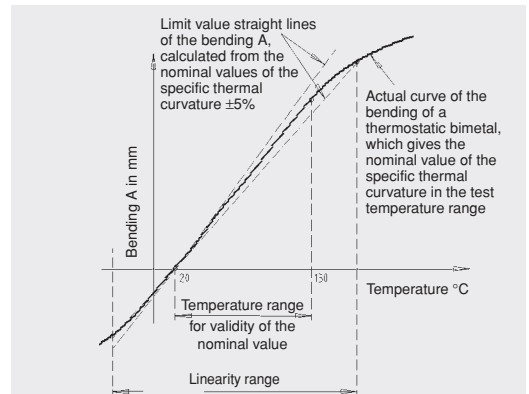
Figure 2.73 Linearity range of thermostatic bimetals

Parameters, errors and error limits

The thermal bending of bimetals varies during production and use. The **zero point position** of the thermometers may already be displaced in the production process, and will certainly be displaced during subsequent use. Such drift can be reduced by suitable heat treatment (aging). The bimetallic springs manufactured for installation are stabilized at a temperature of 650°F to 750°F (350°C to 400°C) - if necessary at even higher temperatures but below their application limit - and are then slowly cooled. The heating and cooling time should not exceed 20 K/min.

The **response** of bimetallic thermometers (without a thermowell) is determined essentially by the heat transfer through the stem, which is in contact with the medium, to the bimetallic spring. The smallest possible distance between the immersion tube wall and spring improves the heat transfer.

Mechanical effects due to unintentional friction in the transmission and indication as well as the actuation of switching contacts may lead to a difference with rising or falling temperature (hysteresis). The helical design of the bimetal spring causes a lifting movement of the pointer and under certain circumstances may cause the pointer to come in contact with the dial or viewing window. However, modern design and production methods help to avoid errors of this type.

Vibration loads make it difficult to read the exact temperature value from the dial. Depending on the requirement and the load, bimetal thermometers can also be supplied with a liquid filling. If high adjusting forces are required with a small sensor length, or if extremely small indicating ranges are needed, the helical spring can also be designed as a two- or multi-turn torsion stage bimetal spring (Figure 2.74).
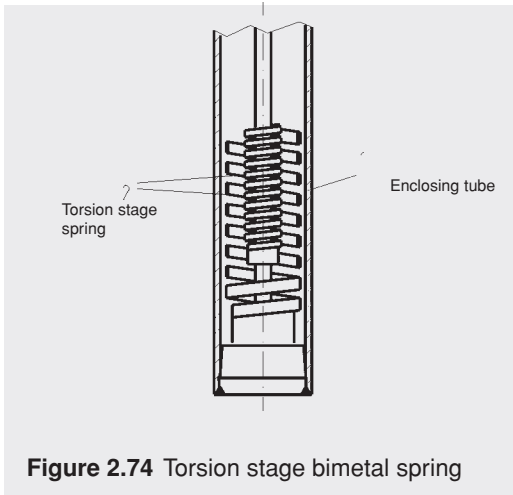
Figure 2.74 Torsion stage bimetal spring

To allow **indication error correction** based on comparison (reference) measurements during operation, the thermometers are often provided with a reset adjustment. Depending on the thermometer type and operating range, this adjustment can be made by an adjustable screw for the bimetal spring, an adjustable pointer, an externally adjustable dial or similar solutions.

Bimetal thermometers are manufactured in with accuracies from ±0.5% to ±1.0% of span per ASME B40.3. Standard ranges for bimetal thermometers are listed in Table 2.18.

Fahrenheit	Dual Scale ∞F & ∞C		Celsius
Single Scale	F Outer,	C Inner	Single Scale
-100/150 F	-100/150 F &	-70/70 C	-50/50 C
-40/120 F	-40/120 F &	-40/50 C	-20/120 C
0/140 F	0/140 F &	-20/60 C	0/50 C
0/200 F	0/200 F &	-15/90 C	0/100 C
0/250 F	0/250 F &	-20/120 C	0/150 C
20/240 F	20/240 F &	-5/115 C	0/200 C
25/125 F	25/125 F &	-5/50 C*	0/250 C
50/300 F	50/300 F &	10/150 C	0/300 C
50/400 F	50/400 F &	10/200 C	0/450 C*
50/550 F	50/500 F &	10/260 C	100/550 C*
150/750 F	150/750 F &	65/400 C	
200/1000 F *	200/1000 F &	100/540 C*	

Table 2.18 Standard ranges for bimetal thermometers

* Not recommended for continuous use above 800°F (425°C)
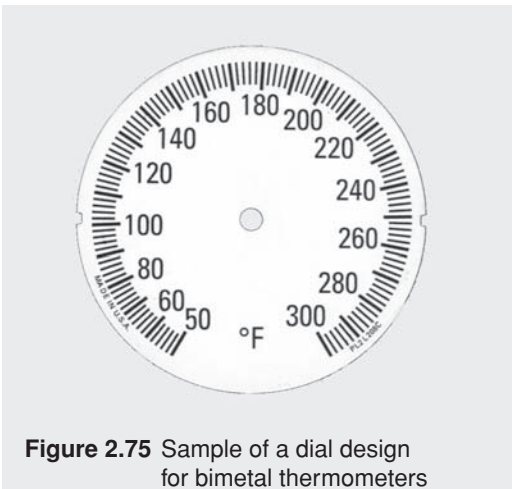
Figure 2.75 Sample of a dial design
for bimetal thermometers

Applications and technical designs

Due to their simple, rugged and inexpensive measuring system, bimetal thermometers are suitable for the most diverse industrial applications, and for this reason they are supplied in many variations. Typical applications are heating, air-conditioning and ventilation systems, machine, plant, tank and pipe construction, and the process & chemical industry.

With additional electrical equipment such as limit signal transmitters, switching contacts etc. (section 1.4.5), they can be combined directly into simple control and regulating processes.

Surface contact thermometers, in which the bimetal spring is housed directly inside the case, are used for temperature measurements on pipes. Other standard types have stems and detachable thermowells either clamped on or held with a set screw.

The stem and associated thermowells are offered in standard lengths and diameters. Those parts in contact with the measured media are made of copper alloys or, in the case of high quality types, of steel or stainless steel. The maximum operating pressure for the thermowell or stem is usually 100 PSI (copper alloys), but can also be up to 400 PSI or higher with suitable selection of material and dimensioning.

Depending on the temperature range the materials used for the case, stem, dial and pointer can be copper alloys, aluminum or plastic. The window is made of acrylic glass or industrial flat glass for higher temperatures. The typical case sizes are from $2^1/_2$" and 6".

Figure 2.76 shows a bimetal thermometer used in HVAC applications.
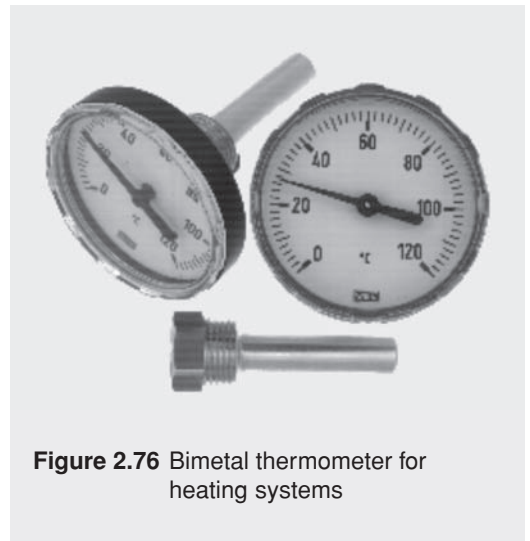
Figure 2.76 Bimetal thermometer for
heating systems

The upper end of the indicating range is extended from 500°F (250°C) to 1000°F (550°C) for **general and high-grade industrial applications** (i.e. for the process industry). These thermometers are designed both with back and lower mount connections. Case sizes range from 1" to 6" and typically have a ±1.0% of span accuracy.

Difficult installation conditions on site mean that it is often practical for the user to install thermometer types with a swivel case. It is recommended that industrial bimetal thermometers are supplied with liquid damping (case and sensor) when they are exposed to vibration. Figure 2.7 shows an industrial type with a swivel case.

industrial types are shown on the basis of the gas pressure spring thermometer. Figure 2.78 shows the external construction of a spring thermometer.

Figure 2.77 Bimetal thermometer for process applications; swivel case

2.6.2.3 Spring thermometers

Spring thermometers indicate the temperature-dependent expansion behavior of a thermometric liquid, the temperature dependent vapor pressure of a liquid or the temperature dependent pressure of a gas via an flexible measuring element. The basic construction of liquid vapor pressure (tension) and gas pressure thermometers is similar. In contrast to other mechanical thermometers, the measuring and indicating point of types with capillary lines may be widely separated. Spring thermometers can measure temperatures from -330°F to 1300°F (-200°C to 700°C). Examples of

Spring thermometer

a) with capillary tube

1 Length of capillary tube
2 Screwed end tube
3 Stem
4 Minimum immersion depth
5 Installation length

b) with neck and thermowell

1.1 Neck
2.1 Protective
3 to 5 as under a)

Figure 2.78 Spring thermometer

Liquid spring thermometers

In the **liquid spring thermometer** the metallic thermometer bulb is completely filled with a thermometric liquid. The measuring spring is connected to the thermometer bulb via the capillary tube. Because of the different thermal expansion behavior between the bulb and thermometric liquid, temperature fluctuations lead to a change in volume, which is picked up by the elastically deformable measuring spring and converted into a change of shape and path. A change in the internal pressure of the liquid on the measuring elements is proportional to a change in volume.

In contrast to pressure gauges, liquid spring thermometers have a closed measuring system. Temperature changes are transmitted virtually linearly into an indication.

A transmission device, such as a linking rod with a segment and transmission gear, transforms the change in shape of the measuring spring into a rotary motion of the pointer. This is typically 270° on circular instruments.

The functional relationship between a temperature change $\Delta t = (t_2 - t_1)$ and the change in internal pressure is represented by the following equation:

$$\Delta p = \frac{(\gamma - 3\alpha) \cdot V_F}{\chi \cdot V + C} \cdot \Delta t \qquad (2\text{-}95)$$

Δp	=	change in internal pressure of liquid
γ	=	coefficient of volumetric expansion
α	=	coefficient of linear expansion of the thermometer bulb
V_F	=	volume of the thermometer bulb
V	=	liquid volume of the entire system
χ	=	compressibility
C	=	constant, designated as volumetric absorption capacity, dependent on the thermometer type

The most important criteria for dimensioning of the thermometer can be determined from this equation.

Starting with measuring springs with the same sensitivity to pressure, the bulb volume must be designed in such a way that the change in internal pressure results in the change in shape of the measuring spring needed for the required temperature range.

The bulb volume must be inversely proportional to the temperature range. Accordingly small temperature measuring ranges require large liquid volumes and large measuring ranges correspondingly smaller sensor volumes.

To keep the measuring errors determined by the temperature behavior of the capillary line and measuring spring small, it is logical to keep the volume of the thermometer bulb as large as possible in relation to the liquid volume in the capillary line and measuring spring.

Thermometric liquids

Liquid spring thermometers can be assumed to have the same thermometric liquid requirements as glass thermometers. This applies to the liquid properties, purity and processing.

Mercury is used as the thermometer liquid of choice for temperature measurements from −30°F to about 1000°F (-35°C to 500°C). This range can be extended to temperatures down to −70°F (-55°C) with mercury-thallium. Thermometers with organic liquids such as toluene and xylene are manufactured for measurements from −20°F to 650°F (-30°C to 350°C).

These organic liquids have a higher thermal expansion coefficient so the bulb volume and thus the sensor dimensions can be made smaller for these thermometer applications.

The effect of air and gas residues on the thermometer reading is eliminated by pressure filling, which already produces a higher pressure at the start of the scale.

With mercury fillings this initial pressure is between 1200 PSI and 1500 PSI, and at the end of the scale - depending on the temperature measuring range and type - from 2000 and 4000 PSI. Thermometers with organic liquids have a filling pressure between 75 and 800 PSI.

Types of construction

If local indication is required, i.e. the measuring and indication points are near each other, the temperature sensor of the thermometer is connected to the measuring element by a short armored capillary tube.

If the temperature value is to be indicated or processed at a remote point, the temperature sensor is connected to the measuring element via a appropriately long capillary tube. Long-distance capillary lines can bridge distances of up to 300 ft. between measuring and indication point.

The **stem** of the liquid spring thermometer consists of the sensor element and a stem extension depending on the application. Installation lengths between 4" and 40" are common. If the stem is immersed directly in the medium to be measured it must withstand the pressure and vibration in the process and be chemically resistant. Material selections and dimensioning of the stem wall are the determining factors in this respect. If thermowells are used, they must be dimensioned according to the specified operating conditions (Section 2.3.2.4).

The required **minimum immersion depth** can be indicated by a mark on the stem or be specified by the manufacturer in the data sheets. It must be observed by the user to avoid too high a measuring error due to axial heat loss.

The required immersion depth depends essentially on the heat transfer conditions of the substance to be measured and on the sensor material and length.

Steel or stainless steel material is generally used for stem capillary lines and measuring springs. The type of alloy depends on the temperature range and specific ambient conditions of the parts of the thermometer.

Carbon steel is used for mercury liquid thermometers, for example, at temperatures up to about 750°F, and high-temperature alloy steels at higher temperatures.

Capillary lines for liquid spring thermometers are made of unalloyed steel. With outside diameters between 0.08 and 0.20 inches the inside diameters of 0.008 to 0.004 inches are kept as small as possible to minimize additional measuring errors due to the temperature effect of the capillary line itself. Capillary lines bend and kink easily and may lead to malfunctioning of the thermometer if a blockage occurs. Therefore capillary lines are painted or provided with plastic, rubber or lead tube sheaths for protection against mechanical damage and corrosion. A flexible spiral metal tube often ensures additional mechanical protection.

The **measuring springs** are made up of spirally wound, flat-rolled precision steel tube. The inside height of the tube is not more than 0.008 inches. The fixed spring end is soldered or welded on to a carrier plate. The free spring end covers a distance between 0.12 and 0.20 inches. The operating principle of these tube springs is similar to that of pressure gauges. It is described in section 1.4.1 Flexible measuring elements.

A **reset adjustment** for fine tuning of the measuring range is provided to change the point of application of the linking rod. Pointer adjusters used to vary the center of rotation on the serrated segment can make zero point adjustments.

The start of the scale can be offset towards higher temperatures by a mechanically pre-stressed measuring spring.

Before final adjustment, liquid spring thermometers are adequately stabilized at the upper temperature limit. A check at regular intervals by comparison measurements is recommended.

Parameters, errors, error correction

For thermometers with **long-distance lines** the temperature effect acts along the capillary line giving an additional source of error.

A further error source is the temperature-dependent **inherent behavior of the measuring spring** determined by the type of thermometer.

Accidental **mechanical deformations** of the stem and capillary line may also lead to a thermometer indicating error.

$$f = \frac{V_M + V_k}{V_f} \cdot \Delta t \qquad (2\text{-}96)$$

f	=	error in Kelvin
Δt	=	change in ambient temperature in relation to reference temperature
V_M	=	effective spring volume
V_K	=	volume of long-distance line with $V_K = q \cdot l$ q - inner cross-section, l - length of long-distance line
V_F	=	volume of thermometer bulb of a liquid spring thermometer
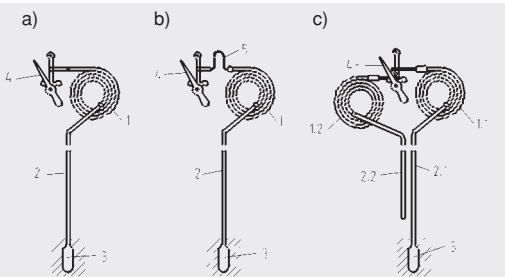
Liquid spring thermometer, arrangements for temperature compensation

a) simple type without temperature compensation
 1. Measuring spring
 2. Long-distance capillary line
 3. Temperature sensor
 4. Pointer

b) with partial temperature compensation (only the effect on the indicating instrument)
 1. to 4. as under a)
 5. Bimetal strip

c) with full temperature compensation (of the effect on long-distance line and indicating instrument)
1.1. Measuring element
1.2. Measuring element for compensation
2.1. Long-distance capillary line
2.2. Capillary line for compensation
3. Temperature sensor (bulb)
4. Pointer

Figure 2.79 Liquid spring thermometer, arrangements for temperature compensation

If an adjusted liquid spring thermometer is used outside its reference temperature, the indicating error caused by the long-distance line and measuring spring can be determined by the relationship defined in equation 2-96. The effect of the measuring spring in liquid spring thermometers with mercury may cause an error of about 0.8% of the indicating range per ±10 K temperature change. The temperature error of the long-distance line per m line length and ±10 K temperature change may be in the order of magnitude of up to ±0.2% of the indicating range.

If the temperature error is not corrected by additional equipment (Figure 2.79a) the total error is obtained from the sum of the error effects of long-distance line and measuring spring.

Partial compensation of the temperature error of liquid spring thermometers can be made by adding as appropriately dimensioned bimetal strip between measuring spring and transmission device (Figure 2.79b).

With correct dimensioning of the bimetal strip and adjustment of the thermometer in the mean temperature range the remaining error can be limited to ±0.05% of the indicating range per 10 K temperature deviation from the reference temperature.

Full compensation of the temperature effects can be achieved if, for example, in addition to the long-distance line a similar capillary is laid, which controls a compensating spring (Figure 2.79c) acting mechanically against the actual measuring spring.

For capillary line lengths up to 100 feet and temperature fluctuations of ±50°F the remaining error is then so small that it can be disregarded. Liquid spring thermometers are calibrated with identical height of sensor and indicating device.

A **height difference** between the sensor and indicating device during operation leads to an additional indicating error, because an additional static overpressure or vacuum acts on the measuring spring. This error can easily be corrected after assembly by re-adjustment of the zero point by the adjustable pointer.

As a result of the elastic deformation, **process pressure effects** on the stem (when used without a thermowell) may lead to measuring errors, which may be up to +0.7% of the indicating range per 1500 PSI overpressure for mercury thermometers.

Vapor pressure spring thermometer

With a construction similar to the liquid spring thermometer, the thermometer bulb of the vapor pressure spring thermometer is only partially filled with a low-boiling-point thermometric liquid.
As long as liquid is still present in the bulb, the vapor pressure in this closed system is dependent only on the temperature. The quantity of liquid has no effect.
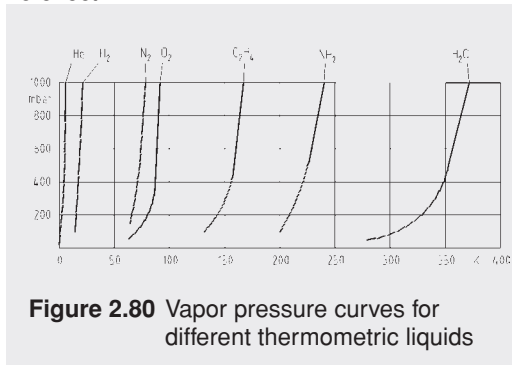
Figure 2.80 Vapor pressure curves for different thermometric liquids

This vapor pressure in the thermometer bulb is transmitted by a capillary tube to the measuring spring, its deformation being determined by the pressure difference between the atmospheric pressure and the temperature-dependent spring internal pressure.
Because of the exponentially increasing **vapor pressure curves**, the scales of the vapor pressure spring thermometer are greatly extended in the high temperature range (Figure 2.80). To make good use of the higher temperature sensitivity at higher temperatures, the measuring range is generally selected in such a way that the temperatures to be measured are indicated in the upper third of the scale. With proper scale graduations, high accuracy readings can be taken.

The bulb design and type of liquid filling may vary depending on the level of the ambient temperature in relation to the temperature of the thermometer bulb.
If the bulb temperature is always below the ambient temperature during thermometer operation, the vapor pressure can be transmitted directly via the capillary line to the measuring element.

Vapor pressure spring thermometer

a) Standard type   b) With bellows in the bulb

F Measuring spring   T Bulb
K Capillary line   Fl Liquid
Z Pointer   D Vapor
                          V Bellows
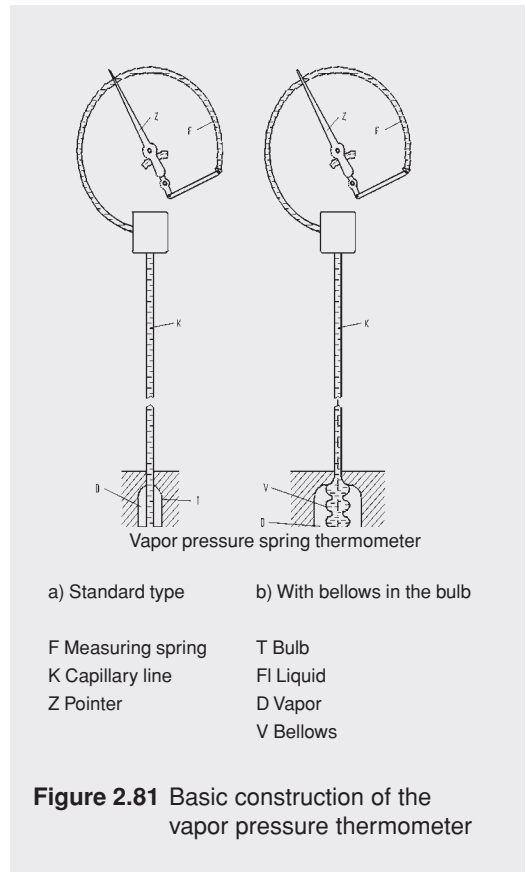
Figure 2.81 Basic construction of the vapor pressure thermometer

In the majority of applications the ambient temperature is lower than the temperature at the start of the measuring range. In such cases (Figure 2.81 a) the capillary line is introduced so deeply into the thermometer bulb that it is always completely immersed in the thermometric liquid even

at the lowest measuring temperature. The pressure is transmitted to the measuring element by the thermometric liquid itself.

For cases in which the ambient temperature may be both above and below the bulb temperature, the vapor phase of thermometric liquid is separated from the transfer liquid by a bellows (Figure 2.81 b).

Thermometric liquids

The thermometric liquid is selected in consideration of the measuring range so that its boiling point is below the temperature at the start of the thermometer measuring range.

The upper temperature is limited by the thermal stability of the liquid and its critical temperature. Examples of common thermometric liquids for vapor pressure spring thermometers and their temperature ranges are as follows:

Propane	-40	to +100°F
Ethyl ether	100	to 380°F
Sulfur dioxide	32	to 320°F
Ethyl alcohol	185	to 470°F
Xylene	300	to 680°F

The liquid quantity and the bulb volume are dimensioned in such a way that at the start of the measuring range the thermometer bulb is filled about 60% with liquid and a liquid residue remains when the upper measuring range temperature is reached.

Parameters, errors, error correction

The **error limits** of vapor pressure spring thermometers are about 1 to 2% of the scale length.

Because of the scale expansion per degree of temperature difference the error diminishes towards the temperature high limit.

Ambient temperature fluctuations do not have an effect when a transfer liquid is used.

Irreversible **mechanical deformations** of measuring sensor and capillary line also do not affect the indication as long as the system remains leak-free and passage to the measuring spring is not completely blocked.

Depending on the vapor pressure prevailing in the system, air pressure fluctuations lead to indication errors, which may be between ± 1 and ± 2 K at the start of the scale and up to 0.2 at the end of the scale with an air pressure change of ± 1 in.Hg. In liquid-filled, long capillary lines the difference in **height** between sensor and measuring spring displaces the zero point of the measuring system. This can be eliminated in the same simple way as with liquid spring thermometers.

Gas pressure spring thermometers

In gas pressure spring thermometers the entire closed system is filled with an inert gas or gas mixture.

The temperature-dependent change in gas pressure is determined via the capillary line and the elastic measuring spring.

For industrial applications the gas filling generally consists of nitrogen or helium. The required filling pressures are 300 to 3000 PSI.

Temperatures between -330°F (-200°C) [critical point for nitrogen –233°F and helium –450°F] and 1300°F (700°C) can be measured with gas pressure spring thermometers. However, most of the technical thermometer types are used from –110°F to about 1200°F (-80°C to 600°C). Greater line lengths up to 300 feet are also available. The smallest measuring span is 60 K for standardized indicating ranges. Smaller measuring spans up to 25 K are feasible with very short capillary lengths and use of a pneumatic transmission system.

Starting from Van der Waal's equation of state for a real gas, the internal pressure of a gas pressure thermometer can be described as a function of temperature.

$$\left(p + \frac{a \cdot n^2}{V^2}\right) \cdot (V - n \cdot b) = n \cdot R \cdot T \qquad (2\text{-}97)$$

p	= gas pressure in the measuring system
V	= gas volume
n	= gas quantity in number of moles
R	= universal gas content
T	= temperature
a, b	= specific gas constants

The constants a and b are gas specific constants, which can be determined experimentally from p-V curves.

The "internal pressure" takes into account the mutual attraction of the gas molecules and the "combined volume" n·b the actual volume of these gas molecules. By inserting these terms in the equation of state of the ideal gas an approximate description of the real gas behavior can be made. If the filling condition (p_0, T_0) and operating condition (p_1, T_1) of a gas pressure spring thermometer are now described by Van der Waal's equation of state, we get an equation system that can be solved via an iterative numerical method. The system pressure of the thermometer can be calculated as a function of the medium temperature taking into account the other system parameters.

For predetermined temperature ranges, the optimum design geometries or volumes for sensors and capillary line and the required thermometer filling pressure can be calculated on the basis of these relationships. A computer program designed for such purposes permits calculation of the optimum filling data directly in production. This allows virtually constant deflection of the measuring spring for each temperature range and facilitates adapted kinematic compensation of the thermometer. The latter is particularly important for small sensor volumes (Figure 2.82).
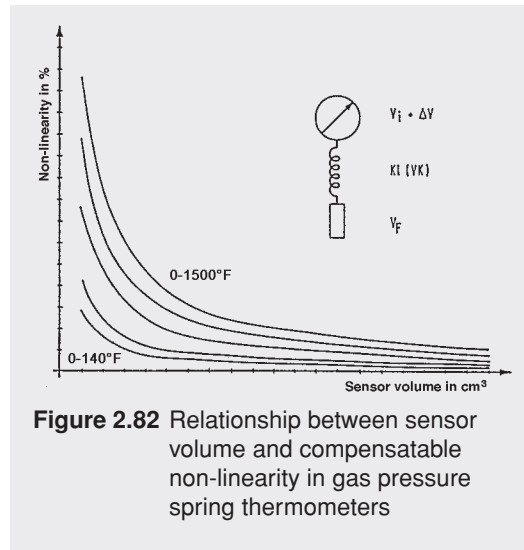
Figure 2.82 Relationship between sensor volume and compensatable non-linearity in gas pressure spring thermometers

Parameters, errors, error elimination

The **scale graduation** of gas pressure spring thermometers is linear over wide ranges as a result of the proportional relationship of gas pressure and temperature.
Non-linearities are due to the non-ideal gas behavior, changes in volume of the bulb and the elastic change in volume of the measuring spring. The effects of **fluctuations in the ambient temperature** can be kept small if the volume of measuring spring and capillary line is small in relation to the volume of the thermometer bulb. In most cases a volume ratio of 1:30 is adequate. Non-linearity and temperature errors are less than 3% for this value. Temperature effects in the measuring spring are minimized by adding bimetal elements to the transmission system.
Barometric effects and height differences between temperature sensor and measuring spring have no appreciable effect on the indication with the high filling pressures used in the gas pressure spring thermometer.

Because of the smaller heat capacity of the filling gases the **reaction time** of gas pressure spring thermometers is shorter than that of comparable types of liquid spring thermometers with mercury filling.

Filling with an inert gas precludes the disadvantages of the liquid and vapor pressure thermometers in the form of possible physiological reactions in the event of equipment failure or destruction.

Operating ranges and technical types

Gas pressure spring thermometers meet high measuring requirements. In addition to general industrial applications they are commonly used for HVAC, chemical and petrochemical, process engineering, industrial and also in the food applications.

Figures 2.83 and 2.84 show examples of industrial types of gas pressure spring thermometers. The thermometers are designed with both back connection and lower mount connection positions. Other connection types are possible.

To improve the flexibility at the installation site, these thermometers can be equipped with swivel stem (Figure 2.85) like comparable bimetal thermometer types. The housing can be rotated through 360° and tilted through 90°.

Thermometers with a non-swivel connection are designed with neck tubes of different length to allow visible installation of the instrument indication outside vessel or pipe insulation.

The **case diameters** are standardized at 2$1/2$", 4", 4$1/2$", and 6" for round instruments and 72 x 72 mm, 96 x 96 mm and 144 x 144 mm for types with a square housing.

Cases with a bayonet ring are generally made of a stainless steel.

The standardized **stem diameters** are 6, 8, 10 and 12 mm. Stem length dimensions are typically between 2$1/2$" and 72". The **maximum operating pressure** at the stem is dependent on type of the material used and its geometry. It is typically 400 PSI for 8 mm diameter stainless steel stems.
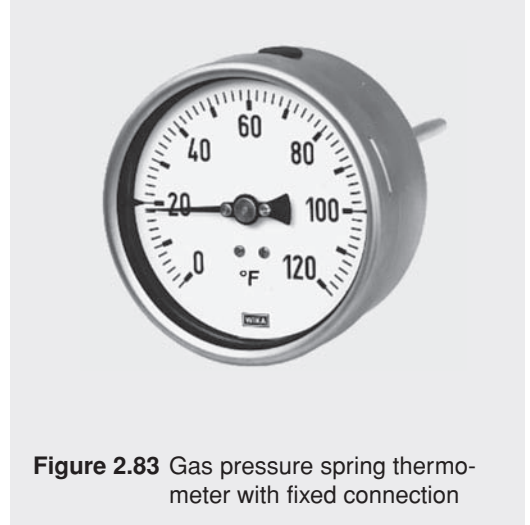
Figure 2.83 Gas pressure spring thermometer with fixed connection

Figure 2.84 Gas pressure spring thermometer with long-distance line

Figure 2.85 Gas pressure spring thermo-
meter with swivel case

The most common **connection types** for gas
pressure spring thermometers are shown in Fig-
ure 2.86 .

Type 1 Design to suit screw clamp, type 4

Type 2 Design to suit protective tubes:
DIN, type BD, BE, BS

Type 3 Design to suit protective tubes:
DIN, type CD, CE, CS

Type 4 with retaining nut and screw clamp

Sealing ring

Figure 2.86 Connection types for gas
pressure spring thermometers
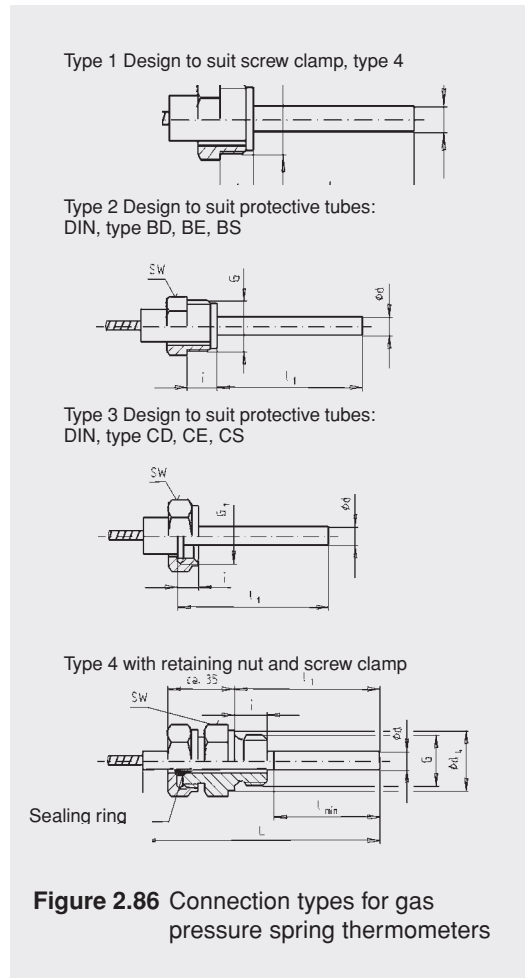
The sensor of a gas pressure spring thermometer
can be well adapted to the specific measuring
task. Figure 2.87 shows a sensor type for surface
temperature measurement on vessels and pipes.
Assembly (Figure 2.88) should be made in such
a way that the surface sensor rests over its full
length on the measuring point.

Figure 2.87 Surface sensor for tempera-
ture measurement on pipes
and vessels
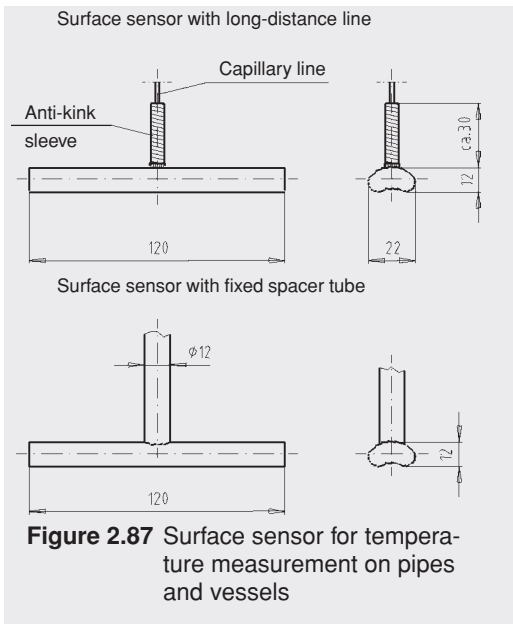
A requirement for reliable measurements is good
thermal coupling to the pipe or vessel wall. To im-
prove the heat transfer a heat transfer compound
can be used for temperatures up to 400°F. To mini-
mize the heat removal error the measuring point
must be thermally insulated.

Figure 2.88 Assembly of an surface
sensor on pipes and vessels
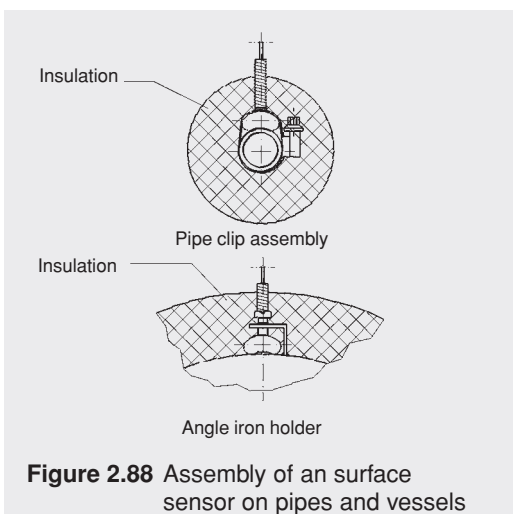
2.7 Electrical thermometers for industrial applications

2.7.1 Platinum resistance thermometers

Platinum resistance thermometers are widely used in industrial measurement systems. Pt 100 resistance thermometers and measuring resistors are standardized according to DIN IEC 751. Their resistance value is 100 ohm at 0°C (32°F). The Pt 100 resistance thermometer conforms to a specified characteristic in a temperature range from -330°F to 1600°F (-200°C to 850°C). Deviations from this characteristic - also known as **basic value set** - are permitted according to two tolerance classes A and B. In tolerance class B, measurement deviations of ±0.3 to 4.6K are permitted according to the temperature. In a temperature range with an upper limit of 1200°F (650°C), deviations of ±0.15 to 1.45 K are allowed in tolerance class A.

Resistance thermometers can generally be divided into three categories:

Industrial Pt resistance thermometers, which are used many in industrial production processes, consist of the standardized components: thermowell, connection head and Pt 100 measuring element. The design of the Pt 100 measuring element conforms to DIN 43 742, its characteristic curve and electrical properties to DIN IEC 751.

Application-related Pt resistance thermometers are thermometers adapted to a specific application, i.e. temperature measurements in wind tunnels, autoclaves, plastic injection molding machines, domestic appliances and thermometers for heat quantity measurement, to mention only a few.

In addition to Pt 100 measuring resistors, Pt 500 and Pt 1000 measuring resistors are also used. Their characteristic conforms to 5 or 10 times the value of the Pt basic value set.

Standard resistance thermometers are the most accurate thermometers and are used accordingly for scientific purposes, i.e. for transferring the International Temperature Scale, ITS 90, in calibration laboratories. In publications dealing with ITS 90, various types of platinum resistance thermometers are specified as standard instruments in the temperature range from -259.35°C to 961.78°C (–434.83°F to 1763.20°F). To achieve the smallest possible measuring uncertainties with standard resistance thermometers (from 0°C to 660°C usually 0.2 to 5 mK) they must be calibrated at the defining fixed points of ITS 90. Their nominal resistance at 0°C is 25 Ω or less and their characteristic curve does not conform to that specified in DIN IEC 751. They are discussed in section 3.2.1.

2.7.1.1 Construction of a platinum resistance thermometer

The temperature-sensitive element of a Pt resistance thermometer is the Pt measuring resistor, which as a rule is permanently installed in a sheath (stem). In some special cases, measuring resistors without a sheath are used, i.e. in air temperature measurements. These will not be considered here. The space between the measuring resistor and the sheath is completely filled with a good heat-conducting material to ensure a short response time and high vibration resistance. A distinction is made between two types of resistance thermometers with cylindrical sheaths.

In the **conventional construction** the bare feed wires are laid in ceramic insulators or in multi-hole ceramic capillaries. The free ends coming out at the end of the ceramic material are welded or brazed to the feed wires of the measuring resistor. The ceramic insulation with the supply leads and the measuring resistor is installed in a metal tube closed at one end with a metal plug, and the remaining cavities are filled with aluminum oxide powder as well as possible. The open end of the sheath is hermetically sealed with an appropriate compound, from which only the supply leads emerge. In the **mineral-insulated sheathed resistance thermometers** a mineral-insulated sheathed cable is used instead of the sheath with
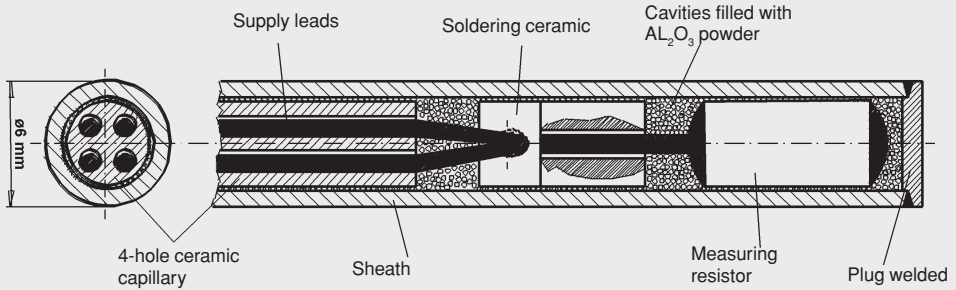
Figure 2.89 Conventionally constructed resistance thermometer
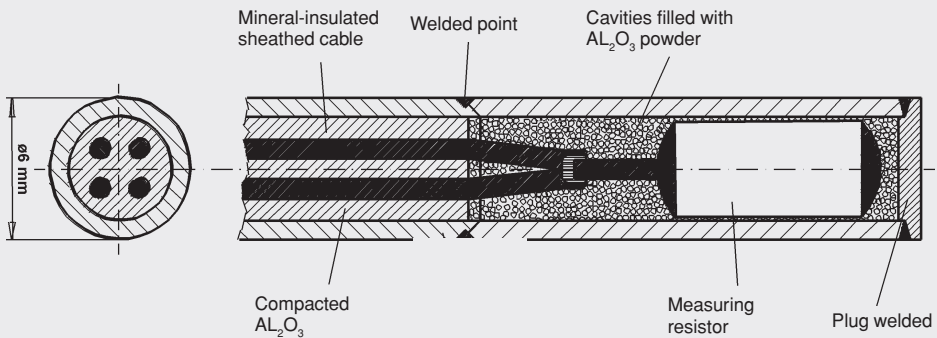
Figure 2.90 Mineral-insulated sheathed resistance thermometer

ceramic insulators and supply leads. Sheathed resistance thermometers have fewer movable parts and are thus more resistant to vibration than the conventional type (see section 2.7.1.4).

Up to operating temperatures of 1000°F (550°C), stainless steel is used for the sheath and copper for the supply leads. Above 1000°F Inconel sheaths and nickel feed wires are used. Either a terminal block is mounted, a plug attached or a cable securely connected at the top end of both types of resistance thermometer.

Resistance thermometers generally have to meet the following requirements: they must be thermally and mechanically stable, respond quickly, have repeatable resistance values, display only slight

aging and always have adequate electrical insulation resistance according to the temperature. The exact electrical requirements are outlined in DIN IEC 751.

2.7.1.2 Platinum RTD's

The **platinum RTD** is the temperature-sensitive element of a platinum resistance thermometer. It consists of the carrier, the measuring winding and the connecting wires. In the first models, an insulated measuring wire was simply wound on to an insulating coil former. These RTD's had limited use because of their high inductance, large dimensions and long response times. Three common types of RTD's with characteristic properties and

different temperature ranges are now widely used: ceramic, glass and film RTD's (see Figure 2.91). Several measuring windings can be installed in one housing in ceramic and glass RTD's.
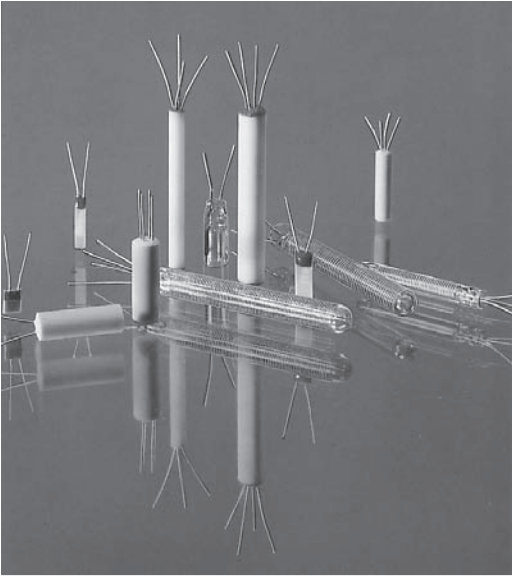
Figure 2.91 RTD's of various types (Heraeus works photo)

Ceramic RTD's

Ceramic RTD's are manufactured as simplex, duplex and triplex types. Typical diameters are 1 to 4.5 mm, typical lengths 25 to 30 mm. They are used for temperatures from –330°F to 1600°F (-200°C to 850°C) and have a double winding. The resistor body consists of a 2-, 4-, or 6-hole ceramic capillary tube, two winding halves of a measuring coil which are located in two adjacent capillaries and welded to each other at one end. Vibration strength can be increased to a limited extent by introducing a powder filling into the capillary. The feed wires are welded to the free winding ends, inserted into the capillary tubes and held

in place with a glaze, which serves as strain relief and housing closure. Ceramic RTD's without a powder filling are the most accurate of their type and supply the most repeatable values because the platinum wire can move freely in the capillary and is not mechanically stressed by the unequal thermal expansion of platinum and ceramic material. There are types with a metal-coated housing, which can be soldered into sheaths to increase the response time. Ceramic RTD's are mainly used for difficult measuring and control tasks in process engineering (see Figure 2.92).

(1) Carrier made of Al_2O_3, (2) Supply leads, (3) Protecting glaze, (4) Pt measuring winding

Figure 2.92 Ceramic RTD
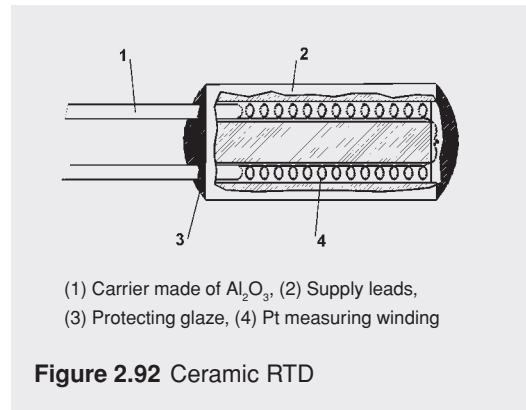
Glass RTD's

Glass RTD's are of the simplex and duplex type. Typical diameters are 1.8 to 5.5 mm, typical lengths 5 to 36 mm. They have a double winding. RTD's are made of hard glass for the temperature range from 32°F to 1000°F (0°C to 550°C). They are highly resistant to vibrations and have a particularly fast response because their measuring winding is just below the surface. They exhibit hysteresis when exposed to rapid temperature changes, in particular during operation below 0°C. Above 300°C (600°F), negative deviations from the DIN basic value set occur because of the increasing electrical conductivity of the glass.

RTD's made of soft glass are used for temperatures from -220°C to 400°C (-360°F to 752°F). They are virtually hysteresis-free and can be manufactured in very small overall sizes, i.e. in bead form with a diameter of 1 mm.

In the production of glass RTD's, a platinum strip is double wound onto a small glass tube. A second thin-walled small glass tube is fused onto the first one, which completely covers the platinum wire in the glass (see Figure 2.93). Therefore they have a particularly fast response and good vibration resistance. Rapid temperature changes lead to stresses and thus to hysteresis because of the unequal expansion of platinum and hard glass. Soft glass RTD's are virtually hysteresis-free because the coefficient of expansion of the soft glass is approximately the same as that of platinum. Glass RTD's extended by fused-on glass tubes can be immersed directly in liquids. Thermometers in chemical plants and in particular thermometers on machines with vibration, i.e. diesel engines, are typical applications for glass RTD's.

(1) Inner glass tube, (2) Supply leads
(3) Pt strip winding, (4) Outer glass tube

Figure 2.93 Glass RTD
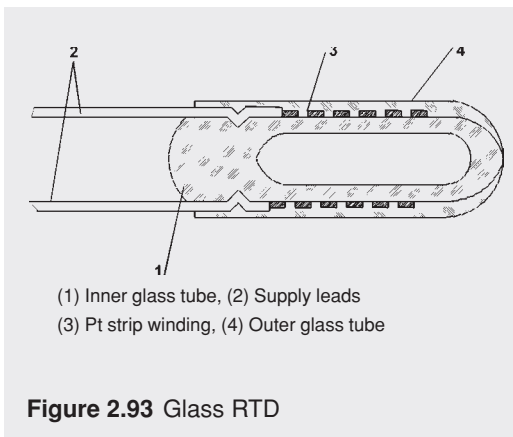
Film RTD's

Thin-film RTD's have a rectangular ceramic substrate as carrier. Typical dimensions are 3 x 4 mm to 3.5 x 12 mm with a thickness of 0.15 mm. They are vibration-resistant and designed as Pt 100, Pt 500 and Pt 1000 RTD's for use in temperatures from 0°C to 500°C (32°F to 900°F). They are manufactured by applying thin Pt films to the substrate surface by vapor deposition or sputtering. Laser or ion etching in such a way that the measuring path has a web-wound shape then structures the Pt film. Compensating sections, which consist of several various-sized, closed loops that can be opened to extend the current path and increase the resistance, are also produced. Before the structured platinum film is sealed with a glass cover for protection, the connecting wires are bonded to the contact areas (see Figure 2.94). Because of their small mass and thus short response time, flat RTD's without housings are used for surface and air temperature measurements. Types with a metallic backing can be soldered on. If a round RTD is required, one or two flat RTD's are embedded in a ceramic pot with a diameter of 2.8 to 4.5 mm.

Thick-film RTD's consist of a flat or cylindrical ceramic substrate onto which the measuring path is applied with conductive pastes by a screen printing process. The conductive paste, a plastic with metal particles, is burned onto the ceramic substrate. The plastic burns away and the metal particles touch each other forming more or less intensive contact zones. Compensation is made by trimming cuts with a laser as on the thin-film RTD. Since the contact zones are relatively unstable under chemical and thermal loads, the operating range is limited to about 0°C to 150°C (32°F to 300°F) and the RTD is unsatisfactory for accurate measurements.

The advantage of thin-film and thick-film RTD's compared to other types is that their production processes can be largely automated and therefore they can be manufactured economically in large quantities.

(1) Web wind, (2) Rough compensation, (3) Fine compensation, (4) Fixing of supply leads, (5) Supply leads

Figure 2.94 Thin-film RTD
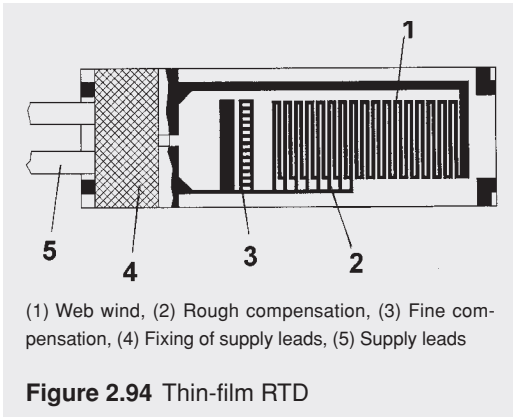
2.7.1.3 Circuitry

The lead wires of Pt 100 RTD's are supplied in lengths of about 10 to 30 mm. This takes into account the DIN basic value set. Further line resistances add errors to the measured value but can be compensated by using suitable connections. A distinction is made between two-, three- and four-wire circuits. In the **two-wire circuit** (Figure 2.95a), supply lead resistances add errors to the measured value. The temperature coefficient of the supply lead causes an error dependent on temperature and thus also on the immersion depth, which cannot be calculated accurately because the supply leads always lie in a temperature gradient. If the manufacturer specifies the supply lead resistance at room temperature, it can be compensated and thus the total error reduced. A two-wire circuit with Pt 100 RTD's is therefore suitable only for very simple measuring applications. With high measuring resistances, i.e. Pt 500 or Pt 1000, the error due to the supply leads is reduced by a factor of 5 or 10, so that they can also be used for accurate measurements, i.e. in heat quantity thermometers.

The **two-wire circuit with loop** (Figure 2.95b) allows compensation of the line resistance because it can be measured via the loop under operating conditions. All four supply leads must be identical. However, this circuit variant has been replaced virtually everywhere by the three-wire circuit. The **three-wire circuit** (Figure 2.95c) is now in standard use on resistance thermometers for industrial applications. Commercially available control, measuring and evaluating equipment is designed for the Pt 100 connection with a three-wire circuit. If the three supply lead resistances are the same, they are compensated by suitable circuitry in this equipment. In the **four-wire circuit** (Figure 2.95 d), supply lead resistances are also compensated if they are different. This circuit is used in laboratories and for particularly demanding applications in industrial measuring systems. A constant measuring current I flows through the RTD and produces a voltage drop U, which is measured at high resistance. As long as the supply lead resistance is small relative to the internal resistance at the voltmeter, it does not add errors.

a) Two-wire circuit
b) Two-wire circuit with loop
c) Three-wire circuit
d) Four-wire circuit

Figure 2.95 Diagrams of four circuit types
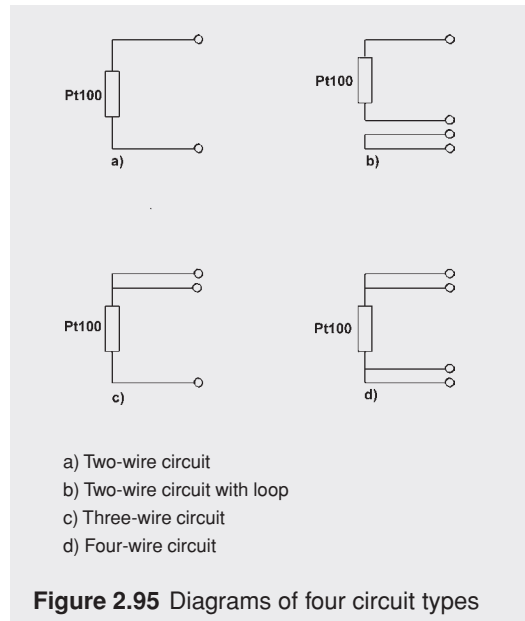
The following table shows resistances and resulting errors for a two-wire circuit with Pt 100 resistance thermometers with different line materials based on a length of 1 m and a diameter of 0.6 mm. The error F_1 applies to the uncompensated line resistance, error F_2 to that compensated at 20°C (68°F).

Material	$R_{(20°C)}$ in Ω/m	$R_{(400°C)}$ / $R_{(20°C)}$	F_1 in K	F_2 in K
Cu	0.06	2.75	0.48	0.30 Ag
0.06	2.70	0.47	0.29	NiCr
2.48	1.086	7.8	0.62	CuNi
1.77	0.996	5.1	0.02	

Table 2.19 Supply lead resistances and measuring errors of typical leads

2.7.1.4 Types of construction

Industrial resistance thermometers with measuring elements

Industrial resistance thermometers consist of the basic components: thermowell, measuring element and connection head. Thermowells and connection heads are described in Section 2.3.2.5.

A measuring element consists of the element tube (sheath), which contains the RTD's and the supply leads, the mounting plate and the connection socket. The sheath can be conventionally constructed with ceramic capillary tubes or, if special vibration strength is required, may consist of a mineral-insulated sheathed cable. The mounting plate with the ceramic terminal socket and the spring-mounted screws is attached on the connection side of the sheath made of stainless steel alloys or stainless steel. The springs under the screws ensure that the measuring element is permanently pressed firmly against the bottom of the thermowell to establish good head contact with the thermowell. Depending on the type of circuit and number of windings of the RTD, up to eight terminals can be mounted on a terminal socket, i.e. 2 x Pt 100 in a four-wire circuit.

Some measuring elements are manufactured without a terminal socket for direct threading to a head transmitter, i.e. WIKA type T21. In addition, various manufacturers offer fast-response measuring elements with a smaller element tube diameter, as well as measuring elements with sheath tapered at the tip (1/4" diameter, tapered to 1/8").
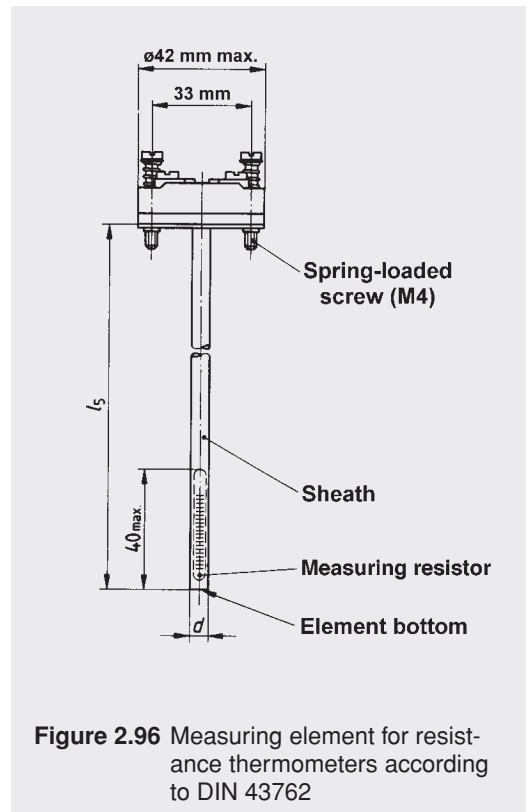
Figure 2.96 Measuring element for resistance thermometers according to DIN 43762
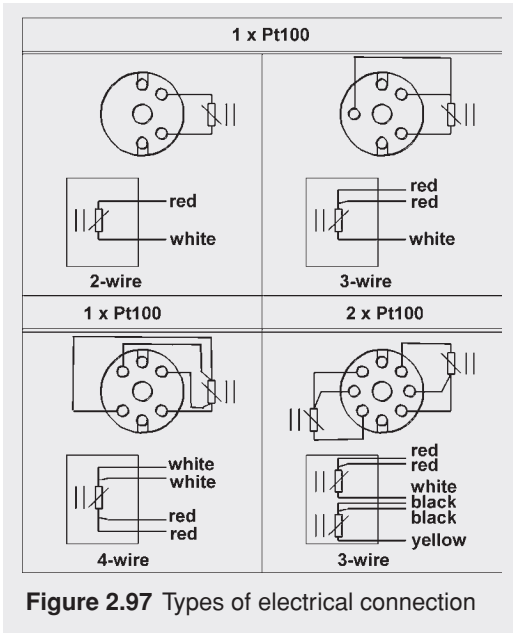
Figure 2.97 Types of electrical connection

Application-rated resistance thermometers

Mineral-insulated resistance thermometer

Mineral insulated cables revolutionized the production of resistance thermometers and thermocouples. They consist of a high-grade steel outer sheath, in which the inner conductors are embedded for insulation in a highly compacted metal oxide, Al_2O_3 or MgO. The starting material is, for example, a metal tube at least 10 feet long with an outside diameter of about 1 to 1.5 inches, into which several cylindrical ceramic parts with two, four or six holes arranged on the same radius are inserted one after the other. The inner conductors, copper or NiCr wire for mineral insulated cables in resistance thermometers or the corresponding thermoelectric wire for thermocouples, are inserted into the holes. Alternate rolling and tempering of the tube and its filling produces a wire, which is finally drawn to the required diameter.

Mineral insulated cables for thermocouples with two inner conductors can be drawn to an outside diameter of just 0.25 mm. The individual ceramic parts are destroyed and compacted to form a homogeneous mass while maintaining the ratio of the diameter of the inner conductor to the outer conductor as well as the spacing of the inner conductors. During this production process, and in particular during further processing into resistance thermometers and thermocouples, the mineral insulated cables must be hermetically sealed at its open ends or stored at a sufficiently high temperature in a heating cabinet because of its strongly hygroscopic metal oxide insulation.

Mineral insulated cables can be manufactured in lengths up to 100 ft., are flexible and allow a bending radius of 2 to 3 times the diameter. They display extremely high mechanical strength and temperature resistance as well as high electrical insulation resistance of the inner conductors between each other and in relation to the outer sheath. Mineral insulated cables for thermocouples with an outer sheath made of stainless steel and a diameter of 1/16th of an inch are used at temperatures up to a maximum of 550°C (1000°F), rising to a maximum of 1200°C (2000°F) for diameters of 1/4 inch and up. Inconel is often used as sheath material for temperatures above 550°C.
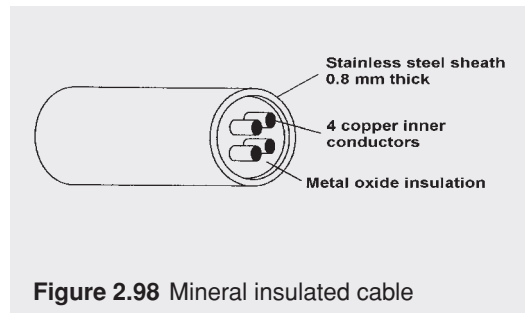
Figure 2.98 Mineral insulated cable

For production of mineral-insulated resistance thermometers the mineral insulated cable is unwound from a coil, straightened, cut to length and the insulation stripped at both ends. At one end the inner conductors of the sheathed cable are welded to the supply leads of the RTD. The other

end is hermetically sealed with a compound while leaving the ends of the feed wires to protrude from the sealing compound. A small metal tube is pushed over the RTD and welded to the sheath. To ensure good heat transfer and to firmly embed the RTD for vibration strength, the free space between the RTD and small tube is filled with aluminum oxide powder before the open end is closed with a plug and welded.

Typical mineral insulated cables for resistance thermometers with an outer sheath made of 300-series stainless steel have diameters of 1/8" or 1/4". Mineral insulated resistance thermometers for temperatures above 550°C (1000°F) are made with Nickel inner conductors; Copper inner conductors are used below 550°C .

Because of their flexibility and small diameters, mineral insulated resistance thermometers can also be used at points which are not easily accessible. A wide variety of connector types is possible, i.e. terminal socket, plug-in connections, or permanently connected cable.

Resistance thermometers for wind tunnels and cold storage rooms

A short response time, reduction of errors due to thermal radiation and adequate mechanical protection of the thermometer are important for temperature measurements in wind tunnels. Therefore thermometers with perforated, high-gloss stems are used. In the interest of short response times, a glass RTD without a housing is located in the stem. A typical operating range is -30°C to 120°C (-22°F to 248°F) ±0.5 K (Figure 2.99).
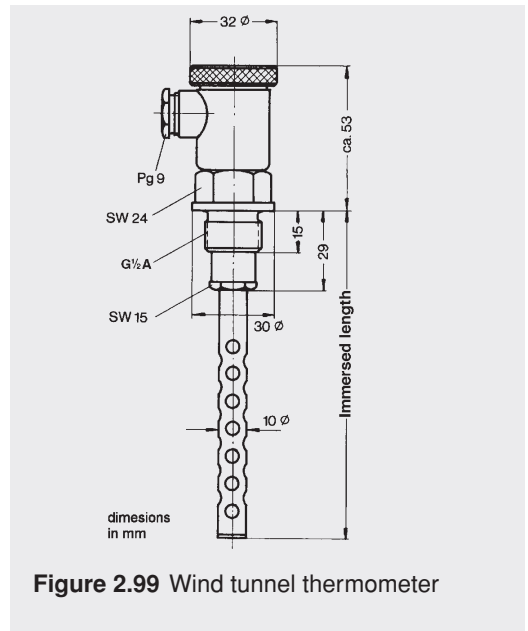
Figure 2.99 Wind tunnel thermometer

Short resistance thermometers with a diameter of 1/4 inch with moisture-tight housing (IP 65) made of light metal or plastic for wall mounting (Figure 2.100) are often used for temperature monitoring in cold stores. The immersion tube has a high-gloss surface for radiation protection. The housing offers space for installing a head transmitter. A typical operating range is -30°C to 70°C (-22°F to 160°F) ±0.5 K.
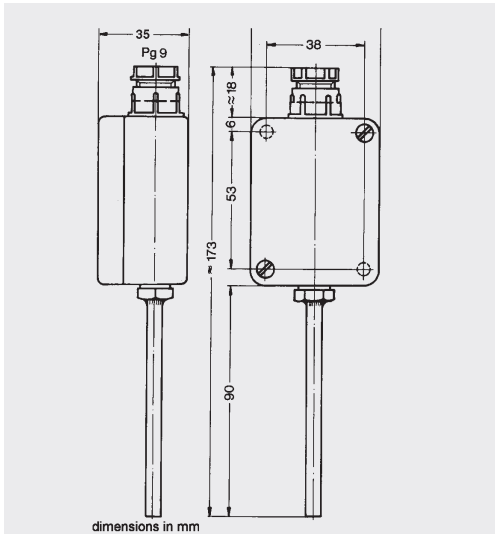
Figure 2.100 Cold store thermometer

Resistance thermometer for autoclaves

The purpose of temperature measurement in autoclaves is to document the temperature curve in relation to time and the maximum achieved temperature. Straight and angled Pt resistance thermometers with diameters of 4.5 and 6 mm are used for temperatures from 0°C to 260°C (32°F to 500°F). The connection point to the silicone connecting cable is vapor-tight, provided with a silicone shrink-on sleeve (S) and designed for pressures up to 47 PSI (Figure 2.101).
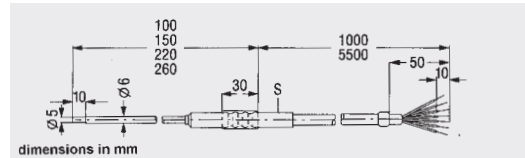
Figure 2.102 Resistance thermometer for autoclaves

Resistance thermometers for heat quantity measurements

For determining heat quantities the temperature differential between feed and return is measured with paired RTD's for temperatures from 20°C to 150°C (68°F to 300°F) with an accuracy of ±0.1 K to 0.5 K. The cable thermometers with Pt 50 and Pt 100 thin-film RTD's used for this purpose must be interchangeable in operation, respond quickly and have a small heat dissipation error (Figure 2.101). In this case the RTD (3) is coupled thermally to the sheath (1) with heat transfer compound. The large-area feed strip (2) also supplies adequate heat energy to the point of transition to the connecting cable (4) so that the heat dissipation from this RTD remains small.

Resistance thermometer for plastics processing

Resistance thermometers of particularly high vibration strength and with bayonet spring are installed in plastic injection molding machines and extruders. They must be easy to remove for cleaning purposes and ensure extremely good heat transfer. The maximum operating temperature is between 300°C and 350°C (660°F), the temperature of the bayonet spring rising to about 200°C (400°F). The feed wires are individually covered as a unit with a glass filament and braided with stainless steel wire (Figure 2.103).

Figure 2.101 Resistance thermometer for heat quantity measurement
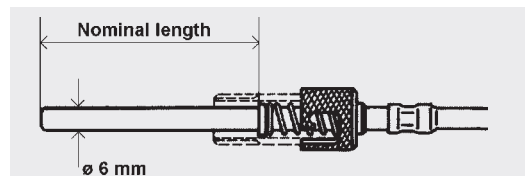
Figure 2.103 Resistance thermometer for plastic injection molding machines and extruders

2.7.1.5 Measuring uncertainties of platinum resistance thermometers

Self-heating error

In resistance thermometers the electric power consumed in the measuring winding leads to a measuring error known as the self-heating error. Its magnitude depends not only on the measuring current but also on the thermal coupling of the RTD to the sheath and on the outer heat transfer between the sheath and measured medium. Since the inner heat transfer in the thermometer cannot be calculated with sufficient accuracy, self-heating errors are determined empirically. With a given outer heat transfer to the thermometer, i.e. in water of constant temperature flowing at 0.4 m/s, the resistances R_1 and R_2 are measured with the measuring currents I_1 and I_2. The outputs are calculated as $P_1 = R_1 \cdot I_1^2$ and $P_2 = R_2 \cdot I_2^2$;

$$U_s = \frac{R_2 - R_1}{(P_2 - P_1) \cdot dR/dt} \quad \text{with } u_s \text{ in K/W} \quad (2\text{-}98)$$

gives the self-heating error u_S, where dR/dt is the gradient of the thermometer characteristics at the test temperature in Ω/K. For temperature measurements in flowing liquids the self-heating error with 1 mA measuring current can generally be disregarded, in static air it is slightly larger than 0.1 K. According to DIN IEC 751, the measuring current should be adjusted in such a way that the power loss $P \leq 0.1$ mW (see also section 2.4).

Instability and aging

Instability and **aging** are effects in the resistance thermometer which lead to non-repeatability. The repeatability of the resistance at the freezing point or triple point of water and the temperature coefficient TC between 0°C and 100°C (32°F to 212°F) are used as evaluation criterion. Instability means a transient change in the resistance temperature characteristic, i.e. by stressing of the platinum wire because of shock, vibration or rapid temperature change. Aging is a long-term effect. Ideally the thermometer changes its characteristic slowly and continuously, as the result of impurities which penetrate the thermometer as far as the measuring winding and contaminate the platinum. These impurities may be alloying constituents of the sheath, i.e. chromium from high-grade steels, or Silicon, which is released from insulating ceramic material in reducing atmospheres and alloys with the platinum. An increasing resistance at the freezing point and triple point and a falling TC are nearly always observed in this case.

Instabilities and aging can be reduced by annealing the thermometer. For this purpose it is exposed for a few hours to a temperature slightly higher than the subsequent operating temperature and then slowly cooled. This process reduces mechanical stresses, and it may also help to reduce the further release of alloying constituents through the formation of oxide films inside the metal sheaths.

Effect of the insulation resistance

The insulation resistance of a resistance thermometer is measured with 10 to 100 VDC between the connections and casing tube according to DIN IEC 751. It acts as a parallel resistance with the measuring winding and leads to reduction of the total resistance and thus to a reduction of the temperature indication. If the insulation resistance at 100°C is only 0.5 Mohm, for example, the following indication error Δt results with the gradient of the Pt 100 characteristic of 0.38 Ω/K at 100°C:

$$\Delta t = \frac{\dfrac{R(t) \cdot R_{isol}}{R(t) + R_{isol}} - R(t)}{dR(t) / dt} \quad (2\text{-}99)$$

$$= \frac{\dfrac{138.5\Omega \cdot 5 \cdot 10^5\,\Omega}{138.5\Omega + 5 \cdot 10^5\,\Omega} - 138.5\Omega}{0.38\,\Omega / K} = -0.1K$$

Moisture, evaporation of conductor materials and the increasing conductivity of all insulation materials at high temperatures can all cause a low insulation resistance. The following table shows minimum insulation resistances for Pt resistance thermometers at room temperature and at the maximum permissible operating temperatures according to DIN IEC 751:

Temperature	Min. insulation resistance
23 °C (73°F)	>100 MΩ
100°C to 300 °C (212°F to 575°F)	10 MΩ
301°C to 500 °C (576°F to 930°F)	2 MΩ
501°C to 850 °C (931°F to 1550°F)	0.5 MΩ

Table 2.20 Minimum insulation resistances according to DIN IEC 751

2.7.1.6 Standardization of industrial platinum resistance thermometers

Industrial Pt resistance thermometers and RTD's are standardized in DIN IEC 751. The standard specifies the basic value set, i.e. the relationship between electrical resistance and temperature, as well as the maximum deviations from the basic value set broken down into tolerance classes. Furthermore, it defines the markings, circuitry and required manufacturer's data, and it also lays down the criteria for routine and type tests on Pt resistance thermometers. These tests are concerned with the establishment of:
- the deviation from the basic value set
- the insulation resistance
- the response times
- the self-heating
- the immersion effect
- the thermoelectric effect
- the effect of a continuous load at the limit temperatures
- the effects of temperature changes.

Additional tests for resistance thermometers under rugged operating conditions are also specified, but in this case only the effect on electrical properties is investigated. These tests include an impact test, vibration test and pressure test.

2.7.2 Thermocouples

Higher measuring uncertainties occur in temperature measurement with thermocouples than with resistance thermometers, but thermocouples can be used over a substantially wider temperature range and are less sensitive to mechanical loads. Depending on the type of element and temperature, thermocouples with non-precious metals exhibit measurement deviations of ±1 K to 9 K in temperatures from -200°C to 1200°C (-330°F to 2100°F), noble metal thermocouples ±1.5 K to 3K in the range from 0°C (32°F) and ±4.3 K at higher temperatures up to a maximum of 1700°C (3100°F). These deviations correspond to the limit deviations for thermocouples according to ANSI MC 96.1 *Standard limits of error*. The basic value sets of the most important thermocouples are also specified in this standard and also in DIN 43710. Reliable temperature measurement requires accurate design for the corresponding process, so it is no surprise to find that thermocouples are also available in a wide range of types. Like resistance thermometers, there are standardized industrial types, which can be designated **industrial thermocouples,** and those designed for specific applications, so-called **application-related thermocouples**.

Standard thermocouples existed in the IPTS temperature scale, which was superseded in 1990 by ITS 90. Platinum-rhodium/platinum thermocouples were specified as standard measuring instruments in the temperature range from 660°C to 1064°C (1220°F to 1950°F). Today this temperature range is covered more accurately by high-temperature resistance thermometers and pyrometers, but the PtRh/Pt thermocouples are still used as a secondary standard. Therefore calibration laboratories are still using PtRh/Pt thermocouples as reference thermometers in the range from 660°C to 1200°C due to their ease of application (see Section 3.2.3.2.).

2.7.2.1 Construction of a thermocouple

In a thermocouple two wires of different material are welded together to form a **couple**, the welded node forming the measuring point. When the measuring point is heated, a voltage approximately proportional to the temperature of the measuring point is measured at the wire ends.

The simplest form of construction of a thermocouple is the so-called **extension cable**. It consists of two wires insulated from each other and welded to each other at one end. Extension cables can be produced with very small diameters and are often used for measurement of surface temperatures. The temperature resistance of the insulation and the oxidation of the wires limit the upper temperature by atmospheric oxygen.

Thermocouples are pre-assembled for typical industrial applications, i.e. the thermocouple is drawn into ceramic insulators and mounted in a sheath. Another variant consists of a mineral-insulated cable with inner conductors made of thermoelectric material. The following illustration shows a conventional non-precious metal thermocouple with small ceramic insulating tube in a metal thermowell with connection head and ceramic terminal socket.

In thermocouples made of precious metals there is risk of "contamination" by impurities, in particular at high temperatures. Hence precious metal thermocouples are made with ceramic inner and outer thermowell, the inner well being made of a gastight ceramic material, i.e. type 710.

2.7.2.2 Circuitry

In the thermocouple, two wires made of different metals or alloys are welded together at the measuring point (c) (see Figure 2.105). The two wires (a) and (b) are called **thermoelectric limbs** and together form the **thermocouple**. If the ends of the thermocouple are connected to copper wires, this connection point is called a **reference point** (d). The thermoelectric voltage measured at the reference point is proportional to the temperature difference between the measuring point and the reference point. Thermocouples can be extended by a **compensating cable** (see section 2.7.2.4) to the reference point. Compensating cables consist of a different material than that of the thermocouple but have the same thermoelectric properties in a limited temperature range. The connection point of the thermocouple and the compensating cable is called the **transition point** (e).

Figure 2.104 Thermo-element with non-precious metal thermocouple
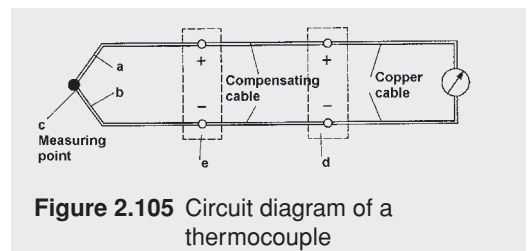
Figure 2.105 Circuit diagram of a thermocouple

2.7.2.3 Thermocouple pairings

Frequently used thermocouples are standardized in DIN IEC 584 and DIN 43 710 and are assigned code letters. The positive limb is always specified first. The basic value sets of the thermocouples

Designation	Type	Temperature range	Signal (µV/K)	Basic value set
Cu-CuNi	T	-250 to 400°C (600°C) -420 to 750°F(1100°F)	23 to 69	DIN IEC 584
Fe-CuNi	J	-200 to 700°C (900°C) -330 to 1300°F(1650°F)	34 to 69	DIN IEC 584
NiCr-CuNi	E	-200 to 700°C(1000°C) -330 to 1300°F(1800°F)	40 to 80	DIN IEC 584
NiCr-Ni	K	-200 to 1000°C(1300°C) -330 to 1800°F(2400°F)	41 to 36	DIN IEC 584
NiCr-Ni	N	-200 to 1000°C(1300°C) -330 to 1800°F(2400°F)	41 to 36	DIN IEC 584
PtRh10-Pt	S	0 to 1300°C(1600°C) 32 to 2400°F(2900°F)	6 to 12	DIN IEC 584
PtRh13-Pt	R	0 to 1300°C(1600°C) 32 to 2400°F(2900°F)	5 to 14	DIN IEC 584
PtRh30-PtRh 6	B	0 to 1600°C(1800°C) 32 to 2900°F(3300°F)	0 to 11	DIN IEC 584
Cu-CuNi	U	-250 to 400°C (600°C) -420 to 750°F(1100°F)	19 to 70	DIN 43710
Fe-CuNi	L	-200 to 700°C (900°C) -330 to 1300°F(1650°F)	30 to 70	DIN 43710

Table 2.21 Operating temperatures and sensitivities of standardized thermocouples.
The temperatures in brackets apply to operation under inert gas, all others to air.

describe the temperature dependence of the thermoelectric voltage.

In addition to the standardized thermocouples there are others for special applications. The best known include the following.

- Iridium/iridium-rhodium (Ir-IrRh40), which is used in neutral and weakly oxidizing atmospheres up to 2000°C (3600°F) for laboratory measurements. The thermocouple consists of rolled, extremely brittle wires, which cannot be bent. Capillary tubes made of the purest aluminum oxide are used for insulation. The thermoelectric voltage is about 10 mV at 2000°C.

- Tungsten-rhenium/tungsten-rhenium (WeRe3-WeRe25) is designed for use in high vacuums and in inert gases up to 2400°C (4350°F). The thermoelectric voltage is about 35.8 mV at 2000°C.

- Pallaplath® (PtRh5-AuPdPt46/2) can be used at temperatures up to 1200°C (2200°F) in air and combines the stability of a precious metal thermocouple with the high thermoelectric voltage of a type K element. The thermoelectric voltage is about 55.4 mV at 1200°C.

Designation	Type	Temperature range	Signal (µV/K)	Basic value set
Ir-IrRh40	-	0 to 2000°C / 32 to 3600°F	3 to 7	-
WeRe3-WeRe25	-	0 to 2400°C / 32 to 4350°F	10 to 19	-
Pallaplath®	-	0 to 1200°C / 0 to 2200°F	29 to 49	by Heraeus
AuFe-Cr	-	-270 to -200°C /-450 to -330°F	16 to 13	-

Table 2.22 Operating temperatures and sensitivities of non-standardized thermocouples

- Gold-iron-chromium thermoelements (AuFe-Cr) are used for low temperature measurements from -270°C to -200°C (-450°F to –330°F). At -270°C the thermoelectric voltage is 4.7 mV.

The basic value sets of these thermocouples are specified by the manufacturer on the basis of individual calibration.

2.7.2.4 Extension cables and compensating cables

An extension cable consists of **thermoelectric wires** with the same alloy elements as contained in the thermocouple. It can be used to manufacture simple thermo-elements with very small diameters, i.e. 0.1 mm, as well as for the extension of thermocouples. Its maximum application temperature is determined primarily by the insulation used. Thermoelectric wires with enamel insulation are used at temperatures up to 100°C (212°F), with PVC insulation at up to 70°C (160°F), with PTFE insulation at up to 200°C (400°F), with spun glass silk insulation at up to 400°C (750°F), and with braided silica fiber insulation at up to 870°C (1600°F).

Over a small limited temperature range, **compensating cables** have the same thermoelectric properties as thermocouples and extension cables, but they differ in the composition of their alloy. Compensating cables are used to extend the thermocouples up to the reference point, i.e. in order to save precious metal. The maximum temperature of the transition point varies and can amount to 100°C (212°F), 150°C (300°F) or 200°C (400°F). Extension cables and compensating cables are standardized in IEC 584 Part 3. The standard lays down an identification system and specifies tolerances and a temperature application range. Correlation of the thermoelectric voltage with the respective thermocouple is based on the compensating cable pair and not on the individual core. Therefore no temperature differences are allowed at the transfer point between the two connections.

2.7.2.5 Reference point compensation

A thermocouple always measures the temperature difference between the measuring point and a **reference point**. If the temperature of the reference point is 0°C, the thermoelectric voltage depends only on the temperature of the measuring point. In the laboratory it may well be possible to adjust the temperature of the reference point to 0°C, i.e. in an ice bath, but for industrial applications this is not generally possible.

Thermocouple reference points at the connection terminals of controllers, temperature indicators, transmitters and recording instruments are at ambient temperature and not at 0°C. The difference between room temperature and 0°C causes a measuring error which is eliminated by reference point compensation. In the case of electronic reference point compensation the temperature of the thermocouple connection terminals at the evaluating instrument in question is measured, i.e. with a Pt 100 RTD or NTC, and an amount equivalent to the terminal temperature is added to the measured thermoelectric voltage. Electronic reference point compensation typically has an error of approximately 0.5 K to 1 K.

A different compensation option takes the form of a **reference point thermostat**, which can be used to hold the temperature of the reference point at, i.e. 50°C (120°F). The resulting error in the thermoelectric voltage measurement is then constant and can be mathematically corrected. Modern thermostats now work with Peltier elements at 0°C and have stabilities of ±0.05 K. In this case there is no need for correction of the reference point temperature.

2.7.2.6 Types of thermocouple design

Technical thermocouples with measuring elements

Technical thermocouples are assembled from standardized individual parts and consist of a thermowell, a measuring element and a connection head. Thermowells and connection heads are

described in section 2.3.2.5. Measuring elements are standardized in DIN 43 735 and are intended for installation in thermoelements. A thermocouple measuring element consists of an insert tube (sheath), which can contain one or several thermocouples, the assembly plate and the connection socket. The internal design of the measuring elements is not laid down in the standards. The insert tube can be made up conventionally of ceramic capillary tubes or, if special vibration resistance is required, it can consist of a mineral-insulated, metal-sheathed cable. The assembly plate with the ceramic terminal socket and spring-mounted screws is attached to the connection side of the insert tube. The springs underneath the screws ensure that the measuring element is permanently and firmly pressed against the bottom of the thermowell, resulting in good heat contact with the thermowell. Depending on the number of installed thermocouples, up to six connection terminals can be attached to one terminal socket, i.e. 3 x NiCr-Ni type K in accordance with DIN IEC 584.

Some measuring elements are manufactured without a terminal socket in order for them to be threaded directly to a head transmitter, i.e. WIKA type T21. Furthermore, various manufacturers offer fast-response measuring elements with a diameter of 1/8" as well as 1/4" measuring elements with a tapered end, tapered from 1/4" to 1/8". In the past, when extremely short response times were required the measuring elements were manufactured with a thermocouple welded at the bottom. This design is called a **grounded junction**. The grounded junction provides fast resonse times, but lacks the electrical isolation of the ungrounded junction.

Figure 2.106 Measuring elements for thermocouples according to DIN 43 735
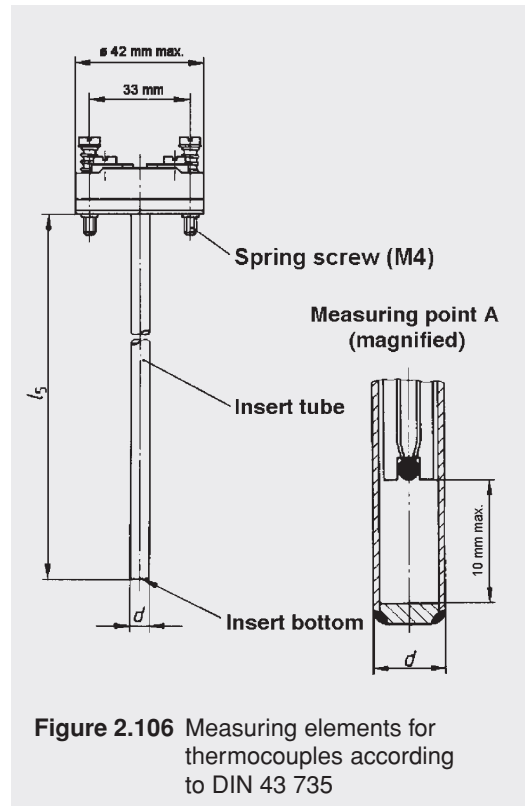
Application-specific thermocouples

Mineral insulated thermocouples

The characteristics and production of mineral-insulated, metal-sheathed cables are described in section 2.7.1.4. Mineral insulated cables and mineral insulated thermocouples are standardized in DIN 43 721. A mineral insulated cable with internal conductors made of thermoelectric material, mostly embedded in MgO or Al_2O_3, is used for the production of mineral-insulated thermocouples. The material is cut to length, bent straight, insulated on one side and hermetically sealed with a potting compound from which the ends of the wire protrude. At the open cable end the metal oxide is removed from the inside of the cable, i.e. with

a fine sand jet, just enough for the exposed internal conductors to be welded together under protective atmosphere to form a measuring node. After the empty space is filled up with the appropriate metal oxide powder, a metal plug is pushed in and welded. Nowadays mineral-insulated thermocouples with MgO insulation can be manufactured with outer diameters of 0.010 inches. The measuring node is then welded under a microscope. Series 3XX stainless steels have proven to be successful sheathing materials up to 800°C (1500°F). Inconel (Figure 2.107) is used from 800°C to 1200°C (1500°F to 2200°F). For precious metal thermocouples the outer sheath can also be made of platinum or platinum-rhodium alloys.

Mineral-insulated thermocouples are extremely resistant to vibration and, thanks to the hermetic enclosure of the thermocouple, they display greater thermal stability. They age less than conventionally designed thermo-elements. They can be manufactured in any length and are flexible enough to be installed even in positions that are difficult to reach.
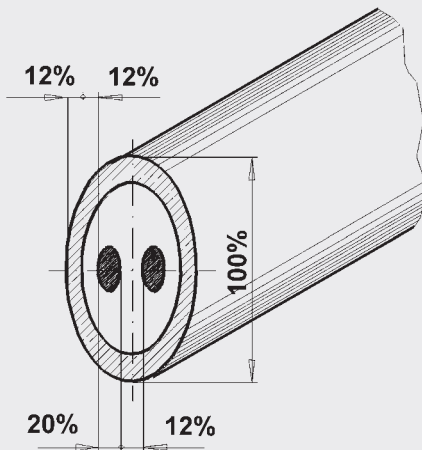
Figure 2.107 Cross-section of a mineral insulated cable

Suction thermocouple for gas temperature measurements

A thermometer senses gas temperatures very slowly because of the poor thermal conductivity of gases. Sometimes large errors occur, therefore, by heat dissipation and radiation. With a suction thermo-element the gas is drawn through an opening in the bottom of the thermowell (3) and comes in contact with the thermoelectric node (1) (Figure 2.108). An additional heater (2) compensates the heat dissipation when the heating current is adjusted so that the measured value is independent of the suction power. A water cooler (7) prevents the entire thermocouple from heating up. (4 Support wires, 5 Insulating rod and 6 Holding tube)
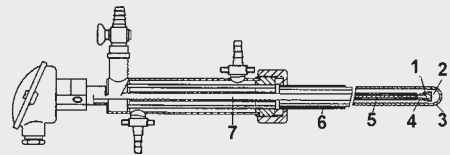
Figure 2.108 Suction thermoelement for gas temperature measurement

Immersion thermocouples for molten steel

Today, measurements in molten steel are almost always taken with **measuring cartridges** (Figure 2.109). In this case the thermocouple (2), usually PtRh-Pt, is inserted in a quartz glass tube (3) and connected to plug contacts (7). An external protective cap (1) protects the sensitive quartz glass tube. To take a measurement the measuring cartridge is plugged on an immersion stem, which is protected by a multi-layer cardboard tube (6). When the stem is dipped into a molten steel bath, the metal cap melts and the molten steel comes into contact with the protected thermocouple. During the measuring operation, which takes around 15 seconds, the plug device and the stem are protected from unacceptable heating by the burning cardboard. The measuring stem can be re-used as soon as the measuring cartridge has been replaced.
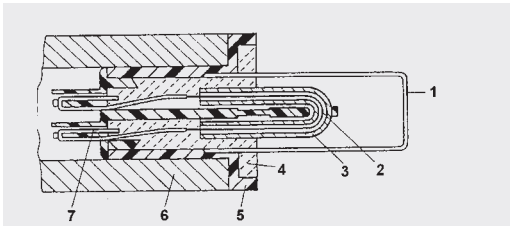
Figure 2.109 Measuring cartridge for molten steel

Precious metal thermocouple for high temperatures

Thermocouples of the type illustrated (Figure 2.110) with PtRh30%-PtRh6% wires (type B in accordance with DIN IEC 584) can be used up to approximately 1800°C (3300°F). The thermocouple is inserted in an insulating rod of ultra-pure aluminum oxide ceramic and is protected from impurities by an internal gastight ceramic thermowell. The outer protective tube consists of porous ceramic with high resistance to cyclic temperature stress. The thermocouple can be installed with a flange according to DIN 43 734, which is threaded onto the steel holding tube. Precious metal thermocouples for high temperatures are used in the glass industry, i.e. at temperatures up to 1500°C (2700°F).
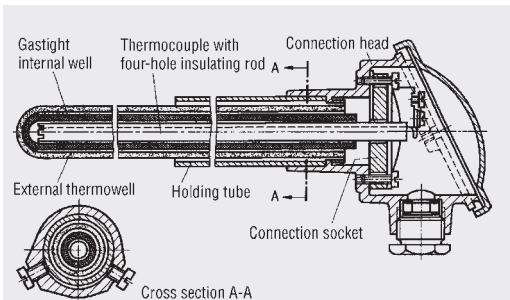
Figure 2.110 Precious metal thermocouple for high temperatures

Angular thermocouples for baths and melts

The thermowell of thermometers used in hardening salt baths and metal melts corrode severely. Furthermore, large temperature gradients at the surface of the melts result in high mechanical loads. With the baths generally heated by directly immersed electrodes, the thermocouples usually have to be of the fast-responding type. On the iron-constantan thermocouples used in salt baths up to 700°C (1300°F), one thermoelectric limb is the iron thermowell while the second thermoelectric limb is formed by an insulated internal conductor of constantan welded to the bottom of the thermowell. The useful life of these thermowells amounts to between 20 and 30 hours. If longer life values are required, it is necessary to use thermowells made of special metals and, i.e. thermowells made of graphite for use in molten metals.
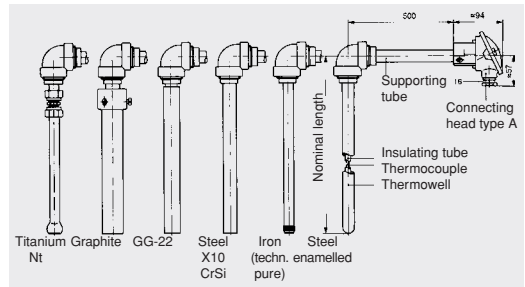
Figure 2.111 Angular thermocouples for baths and melts

2.7.2.7 Measuring uncertainties of thermocouples

Errors due to aging

Thermocouples age and change their temperature/thermoelectric voltage curve. Type J thermocouples (Fe-CuNi) and T (Cu-CuNi) age slightly because the pure metal limb oxidizes. As for Type K and N thermocouples (NiCr-Ni), considerable changes of thermoelectric voltage can occur at

high temperatures due to chromium depletion in the NiCr limb, which results in a decreasing thermoelectric voltage. This effect is accelerated if there is a shortage of oxygen, because a complete oxide skin is unable to form on the surface of the thermocouple and hinders further oxidation. The chromium oxidizes but not the nickel, giving rise to the **green rot** that destroys the thermocouple.

The Ni limb is often damaged by sulfur, which occurs in flue gases for example. During the fast cooling of NiCr-Ni thermocouples, which were operated at temperatures above 700°C (1300°F), certain states within the crystal structure (short-range order) are frozen, which in type K elements can result in a change of thermoelectric voltage of up to 0.8 mV. It has been possible to reduce the **short-range order effect** in NiCr-Ni thermocouples type N (nicrosil-nisil) by alloying both limbs with silicon. The effect is reversible and is largely cancelled again by annealing above 700°C with subsequent slow cooling. Thin sheathed thermocouples react in this respect with particular sensitivity. Even cooling in still air can cause deviations of 1 K.

Investigations on aging-in-air conducted by the the companies Vacuumschmelze and Heraeus on NiCr-Ni mineral insulated thermocouples with a diameter of 3.2 mm and an Inconel outer sheath found that an initial aging of approximately 1 K within the first 10 hours was followed by changes of only about 1 K during the medium life span of the thermocouples (approximately 2,300 hours). Larger deviations did not come up until after deoxidation of the outer sheath.

PtRh-Pt thermocouples of types R and S display practically no aging up to 1400°C (2550°F), but they are highly sensitive to impurities. Silicon and phosphorus destroy the platinum very quickly. Silicon, which in the presence of Pt can be released from insulating ceramics even in weakly reducing atmospheres (reduction from SiO_2 to Si), alloys with the Pt limb of the element and causes measuring errors of 10 K and more even in quantities of a few ppm. Production has to proceed, therefore, with very great care.

Errors due to inhomogeneties

Physical and chemical **inhomogeneties** in thermocouples may corrupt the thermoelectric voltage under certain conditions. These inhomogenities are caused in thermoelectric wire i.e. by the absorption of impurities from the surroundings, the exchange of alloying elements, recrystallization, phase transformations and the depletion of specific components, particularly at high temperatures.

Inhomogeneties are bound to arise during the production of thermocouples. However, they will only corrupt the measurement result when they fall within an inhomogeneous temperature field, i.e. in a temperature gradient. Furthermore, areas of inhomogenety arise in thermocouples of type J (Fe-CuNi) due to bending and kinking, and in types N and K (NiCr-Ni) due to overheating. If these thermocouples are to be used at temperatures below 600°C (1100°F), it is possible to cure the areas of inhomogenety by pre-aging at 700°C (1300°F) with subsequent slow cooling. Bending and kinking causes areas of inhomogenety in PtRh-Pt thermocouples. It is necessary, therefore, to anneal these thermoelectric wires for 2 to 3 minutes prior to their installation in the protective fitting.

Errors due to the reference point and compensating cable

The DIN basic value sets for thermocouples are based on a reference point temperature of 0°C. A deviation Δt of the reference point temperature results therefore in an error. Because of the non-linearity of all the thermocouple characteristic curves, a deviation of, i.e. 50°C from the reference point temperature will not result necessarily in a measuring error equal also to 50°C. Allowance for a reference point temperature that deviates from 0°C is made with a correction factor k, which is added to the measured temperature t(Uth). In the following example, a type S thermocouple measures 900°C at a reference point temperature of 50°C in accordance with the DIN basic value sets. The temperature t at the measuring point can be

calculated as follows:

$$t = t\,(U_{th}) + k \qquad\qquad (2\text{-}100)$$

and

$$k = \frac{(\,dU_{th}\,/\,dt\,)_{ref}}{(\,dU_{th}\,/\,dt\,)_{meas}} \cdot \Delta t$$

where

$$t = 900°C + \frac{0.006\,mV/K}{0.012\,mV/K} \cdot 50°C = 925°C$$

where: $\Delta t = t_{Vgl} - 0°C$ is the deviation from the reference point temperature of $0°C$, $(dU_{th}/dt)_{ref}$ is the gradient of the thermocouple curve at the reference point temperature t_{ref}, and $(dU_{th}/dt)_{meas}$ is the gradient of the thermocouple curve at the measuring point temperature t_{meas}. Since the gradient of the thermoelectric voltage curve at $50°C$ is only half as great as at $900°C$, the deviation of the reference point temperature has only half the impact, but it still cannot be neglected.

The combination of compensating cables and thermocouples may result in a doubling of the possible measuring error when the compensating cable and the thermocouple exhaust the acceptable tolerance range. **Example**: a thermocouple type K, standard limits of error, measures $500°C$ in a furnace. The connecting head with transfer point has a temperature of $100°C$. The acceptable error for temperatures from -40 to $1200°C$ according to ANSI can amount to $2.5°C$ or $0.0075 \cdot t$, whichever value is higher. At the upper limit of tolerance class 2 the thermocouple is allowed to deviate by 3.75 K and the compensating cable by 2.5 K, resulting in an overall error of 6.25 K. The only solution in this case is a combination of calibrated compensating cables and thermocouples with measurement deviations of differing signs.

Errors due to galvanic currents and faulty insulation resistance

When two wires of different material come together with an electrolyte, they form a **galvanic element**. Care must be taken, therefore, to ensure that insulating materials in thermocouples and the insulating material of compensating and extension cables do not absorb any moisture. Although galvanic elements display a high internal resistance and are shorted over the extension cables, they can still cause errors of several K because galvanic voltages are approximately 100 times bigger than thermoelectric voltages.

Poor insulation of the thermocouple and/or the compensating cable generally results in a reduction of the temperature reading. Insulation errors occur in mineral-insulated sheathed thermocouples primarily as the result of moisture in the hygroscopic metal oxide powder. This moisture was either trapped inside from the beginning due to poor production or penetrated the inside of the sheathed cable at some later time through leaky weld seams or at the supply wire bushing. At high temperatures the increasing electrical conductance of the insulation materials causes the insulation resistance to decrease (see Figure 2.112).

Insulation resistance of mineral insulated thermocouples

'TYP_S32.DAT'
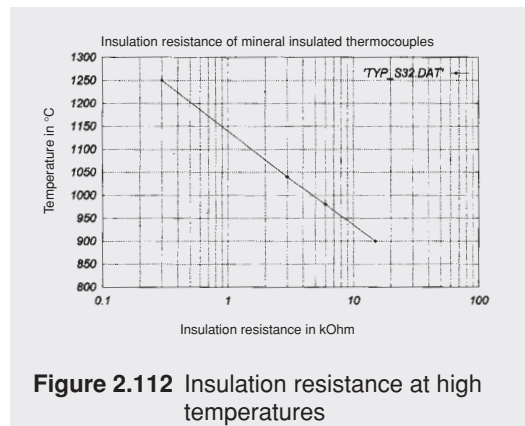
Figure 2.112 Insulation resistance at high temperatures

The results are short-circuiting and the formation of a new thermocouple whose internal resistance equals the insulation resistance. The thermocouple thus formed only corrupts the measurement result, however, when its temperature is higher than the temperature at the measuring tip of the element. In the event of overheating of the thermocouple between the measuring point and the transfer point or reference point, the measurement error depends on the insulation resistance as well as on the conductor resistance of the element. Since the insulation resistance of the mineral insulated cable depends on its temperature and not on its diameter, thicker mineral insulated cables with thermoelectric wires of larger diameter result in smaller measurement errors due to their lower conductor resistance (see Figure 2.113).
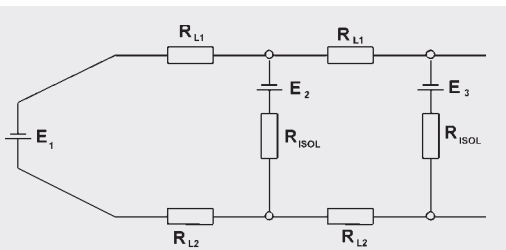
Figure 2.113 Equivalent circuit diagram for analysis of the insulation characteristic

2.7.2.8 Standardization and validation

Basic value sets and tolerance classes

The basic value sets of thermoelectric voltages for elements of types J, T, E, K, N, S, R and B are standardized in DIN IEC 584-1. In DIN IEC 584-1 the thermoelectric voltages are listed in table form as a function of temperature and the temperature as a function of thermoelectric voltage. In addition the standard specifies coefficients and polynomials for calculating these tables. The thermoelectric voltages quoted in both standards are always related to a reference point temperature of 0°C.

The acceptable limit deviations of the thermoelements are laid down in DIN IEC 584-2 in 3 tolerance classes. The limit deviations apply for thermocouples as supplied by the manufacturer; no allowance is made for a change of thermoelectric voltage during subsequent operation.

The extension cable and the compensating cable are standardized in IEC 584-3. The original title is "Extension cables - tolerances and identification system". The first section of the standard defines the terms extension cable and compensating cable and lays down an identification system. Accordingly, extension cables are to be marked with an X (extension cable) after the element's type designation, i.e. JX and KX for extension cables of element types J and K. Compensating cables

Class	1	2	3 [2]
Limit deviation (±) [1]	0.5 K or 0.004 * I t I	1.0 K or 0.0075 * I t I	1.0 K or 0.015 * I t I
Application range type T	-40°F to 660°F	-40°F to 660°F	-330°F to 100°F
Limit deviation (±)	1.5 K or 0.004 * I t I	2.5 K or 0.0075 * I t I	2.5 K or 0.015 * I t I
Application range type E	-40°F to 1500°F	-40°F to 1650°F	-330°F to 100°F
Application range type J	-40°F to 1400°F	-40°F to 1400°F	—
Application range type K	-40°F to 1800°F	-40°F to 2200°F	-330°F to 100°F
Limit deviation (±)	1 K or {1+(t-1100) * 0.003} K	1.5 K or 0.0025 * t	4 K or 0.005 * t
Application range type R, S	32°F to 2900°F	32°F to 2900°F	—
Application range type B	—	1100°F to 3100°F	1100°F to 3100°F

[1] Values specified in K or percentages based on the actual temperature in °F apply as limit deviation.
[2] Thermocouples and thermoelectric wires are usually delivered in such a form that the limit deviations quoted in the above table are observed for their temperature ranges above -40°F. Deviations for thermocouples of the same material may be larger at temperatures below -40°F than the limit deviations specified in Class 3. If thermocouples are required to comply with the limit deviation in accordance with Class 1, 2 and/or 3, this must be quoted on the order, in which case special selection of the material is usually necessary.

Table 2.23 Limit deviations of thermoelectric voltages, excerpt from DIN IEC 584-2

are to be given the suffix C, CA or CB (compen-
sating cable), where the letters A and B define
maximum temperatures of the transmission point
and different tolerances. The second section of
IEC 584-3 specifies a color coding system for the
positive conductor and the outer sheath of the
cable.

Calibration of thermocouples

ANSI MC96.1 (1975) specifies the conditions and
error limits for calibration. They also the maximum
application temperatures for thermocouples. Ther-
mocouples can be validated in two accuracy
classes (standard or special) according to their
maximum application temperature.

2.8 Outlook and development trends for industrial temperature measurement

Temperature measurement has a long tradition and will continue to play an important role in metrology in the future.

Relentless pressure on production departments to optimize the economic efficiency of manufacturing processes normally manifests a higher level of plant automation. Optimization of the manufacturing process requires an even more exact control of process parameters. For this reason there is likely to be a steadily rising need for industrial temperature sensors.

The demand for industrial thermometers is also being fueled by tougher environmental laws and stricter product standards in critical manufacturing processes. Mandatory documentation as required, for example, in the heating and ventilation field and ISO 9000, is also resulting in more and more temperature measurements having to be taken as well as other process variables.

On the other hand, rising pressure leads to measurements only being taken where they are absolutely essential. In the case of bearing sleeves, for example, an exact knowledge of the system allows the entire temperature distribution in the bearing to be calculated from a single temperature measurement. The additional thermometers previously required are now unnecessary.

On the whole the demand for temperature sensors is rising, though the requirements on industrial temperature metrology are changing and shifting.

The increasing rationalization and integration of manufacturing process control and planning systems calls for appropriate measuring systems. For these measuring systems it is necessary in turn to provide uniform, standardized and producer-independent electrical, mechanical and electronic interfaces and user environments. The process industry is unable to provide separate electronic and user training courses for each measuring sensor. Basically, the uniform adjustment interface for analog measurement transducers was formed by the potentiometer and screwdriver. If an intelligent pressure measuring transducer is used in a plant with the bus protocol from company A, it ought to be possible to operate this measuring transducer with the same configuration unit as temperature measuring transducers with an identical bus protocol from company B. The continuing debate about field buses and the standardization of software user environments shows that this requirement is not to be taken for granted and that its implementation is occurs very slowly. This incompatibility of measuring system interfaces is one of the reasons for the hesitant introduction of field buses. The tendency of large companies to opt for a few, standardized thermometers and sensor types is a further reflection of this. The forces of harmonization will prevail in temperature metrology as they have elsewhere.

New and optimized manufacturing processes are making greater use of the temperature scale in the upper and lower range. Exhaust gas catalysts work at temperatures of 1500°F to 1800°F (800°C to 1000°C). High-temperature superconductors, which can be used at -420°F to -300°F (-250°C to -180°C) and higher, are also being increasingly used in industry. The temperature probes used in these applications have to work reliably and steadily under higher loads and stresses. This calls for the development of new temperature sensor principles or the further development of existing temperature sensors into improved industrial temperature probes. A basis for such developments can be provided by the discoveries made in physics during the past few years. An example of such technological innovations are **s**uperconducting **qu**antum **i**nterference **d**evices (**SQUID**s). The use of SQUIDs in medicine, geophysics and material testing has already begun to fundamentally change metrology.

New materials, material combinations and processes pose new challenges for temperature metrology and the technical equipment of temperature probes. Two examples can be cited as representative: the food industry's demand for cleaning of process pipework by mechanical processes requires a change in the mechanical design of the temperature sensor. Processes in biotechnology are only possible with very tight tolerances and extremely clean surfaces. An absolute error of approximately 1 K at 212°F or up to 5 K at 1100°F is the current the state of the art. In enzyme technology deviations of as little as 0.1 K from the correct process temperature can lead to rejection of up to 10 % of the product.

Increasingly problems of electromagnetic compatibility (EMC) and cost reasons are transferring the processing of measurement signals by measuring transducers from the control room into the field. There is a distinct trend in temperature metrology to reduce the size of the control cabinet, which was equipped with busbar measuring transducers, or to do away with it altogether and replace it with on-site head transmitters.

For conformance with the European CE requirements and for ISO 9000 traceability, far more measuring sensors have to be installed than has been the case so far. The observance of tight and standardized tolerances and the high quality demanded in production requires high-technology but low-cost production for mass use. Extremely economical production of the temperature sensors and their processing electronics is necessary. This demand can only be met by exhaustive exploitation of modern technologies. It seems likely, therefore, that the integration of sensor and electronics on a high-temperature silicone or ruby base will be established in measurement ranges up to approximately 350°F and possibly even to 500°F.

There are also signs of a further trend for the temperature metrology sector. Sensor temperature is the most important correction variable for many sensors of other measurement variables. This applies in particular to sensors based on organic chemistry. In these cases the sensor element for the temperature measurement is also integrated. The temperature measurement is thus delivered as a "side product" for follow-up intelligent processing by the microprocessor. In other words, temperature becomes "one of many" measured values. Similarly, the networking of sensors with a field bus means that the temperature measuring sensor is no longer a single special isolated measuring point - in spite of all its special conditions of use - but part of an entire network.

These new conditions of application are well illustrated by comparison with human biology. The touch sensors, temperature sensors and pain sensors in the skin, although individually specialized, add up to a uniform network with compatible interfaces that can only provide the necessary information when working together. No single manufacturer of sensors is able to produce all types economically. There is mounting pressure, therefore, for sensor manufacturers to cooperate and standardize. This is the only way to be able to serve each industrial branch with its characteristic combination of probes and sensor types economically and with the know-how needed in this sector.

3 Process engineering requirements for pressure and temperature measurement

3.1 Signal processing and transmission in the measurement chain

Sensors which transform a physical process variable such as pressure or temperature into an electrically measurable quantity such as resistance, voltage, current or capacitance will be referred to here as **electrical sensors**. All the electrical sensors described here have one thing in common: they generate or convert very little energy, because otherwise the measurement readings would be corrupted. Furthermore, the mathematical relationship between the measured physical

variable and the generated electrical value is defined individually for each sensor type. The consequences this has for further processing of industrial measurement signals are described in the following subsections.

The measured physical value is transmitted as an electrical measurement signal via a **measurement chain** (see Figure 3.1) for further processing and to control the production process.
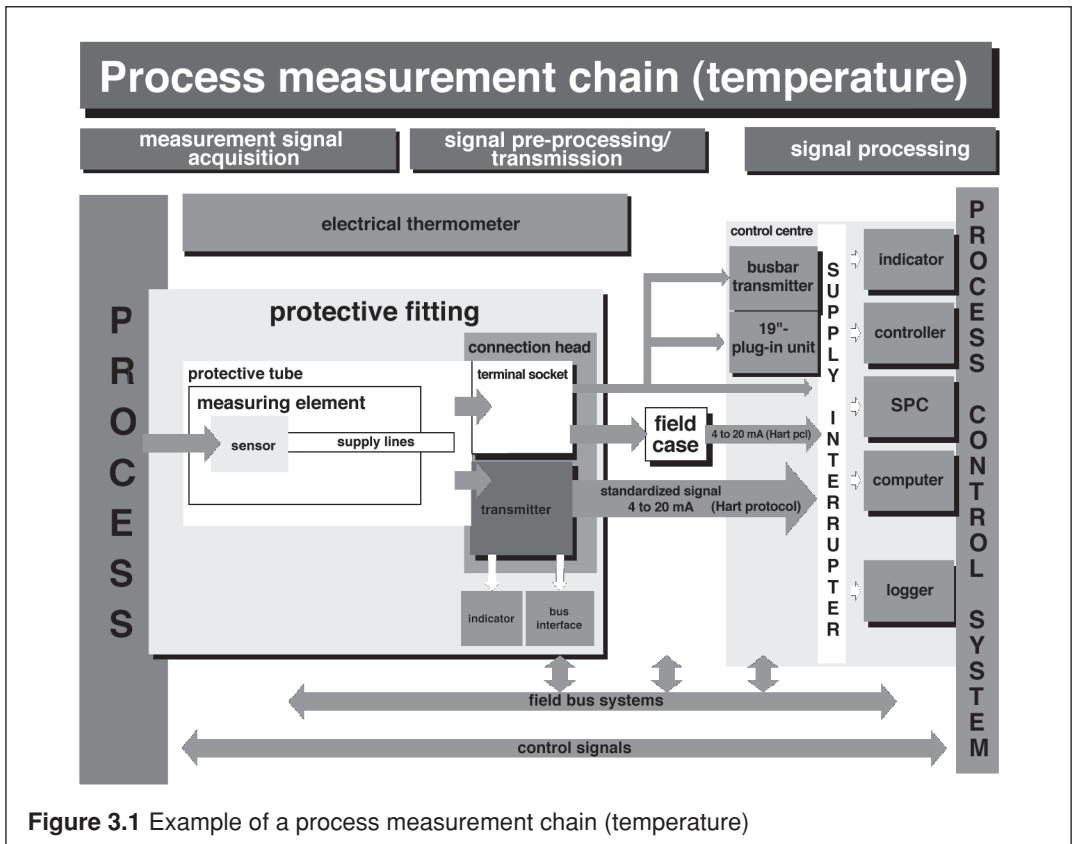
Figure 3.1 Example of a process measurement chain (temperature)

The first step is always to collect the sensor's electrical measurement signal. This includes amplifying, standardizing and transforming the measurement signal into signals that are suitable for processing and transmission and into electrical and mathematical forms of representation. If head transducers are used, this transformation can take place very close to the production process. In other cases the measurement signal is first transmitted into the control center for further processing with busbar transducers or 19" plug-in transducers. The process control system, SPC or controller closes the control circuit with control signals that are fed back to the actuators in the production process. Those components designed to process the sensor-supplied measurement signal in this process measurement chain are described in the following subsections.

3.1.1 Transducer signal conversion

3.1.1.1 Basic measuring methods for electrical sensors

Resistance

Resistance sensors (see Section 2.2.3.2) can take measurements in three ways. Since a resistor supplies no electrical energy of its own, it is always necessary for energy to be supplied externally by an electrical measuring circuit.

Resistance measurement with constant current

A voltage drop produced at a resistor by a constant current is a direct measure of the resistance.

Ohm's law:
$$U = R \cdot I$$

Since I is constant, U must be proportional to R. The advantage of the constant current method is the extreme ease with which it is possible to process the linear relationship between voltage and resistance. Errors due to the supply line resistances can also be compensated with constant current (see Section 2.7.1.3). Measuring with constant current is the classical method with Pt 100 sensors. One disadvantage, however, is the relatively high effort required to produce an exact and stable constant current source.

Resistance measurement with constant voltage: the resistor is connected to a constant voltage source. The current flowing through the resistor is a measure of the conductance 1/R.

It is very easy to compensate errors due to supply line resistances by control engineering means. The constant voltage method is preferred for high-resistance sensors and for measurements with a follow-up processor. It should be noted, however, that the reciprocal relationship 1/R between current and resistance requires more effort to process, i.e. a processor is needed for the conversion.

Resistance measurement with a resistance bridge

Another alternative is to use a resistance bridge, which presents the resistance being measured in relation to a known resistance (see Section 1.3.2.2).
Its advantage is the ability to compensate temperature drifts of the measuring bridge or sensor by incorporating a temperature-dependent resistor in the bridge. In this case we talk of a **compensated measuring bridge.**
Compensated and non-compensated resistance bridges are used in electrical pressure measurement (Section 1.3.2.2).
Satisfactory compensation of line resistances in a measuring bridge is difficult, however, when the lines to the sensor are long (which is the rule in temperature measuring systems).

Voltage

There is no need to supply any additional power to voltage-generating sensor elements for measurement purposes. Two methods are in widespread use.

Direct measurement of voltages

In voltage-generating sensors such as thermo-couples or piezo-sensors, the generated voltage can be measured directly.

It is possible to take direct measurements with a very simple and economical measuring circuit. On the other hand, these voltage sources may possess a high internal resistance, resulting in a voltage drop and therefore corruption of the measurement reading when the measuring current is tapped from the sensor.

$$U_{fault} = \frac{R_i}{R_i + R_L} \cdot U_{sensor} \qquad (3\text{-}1)$$
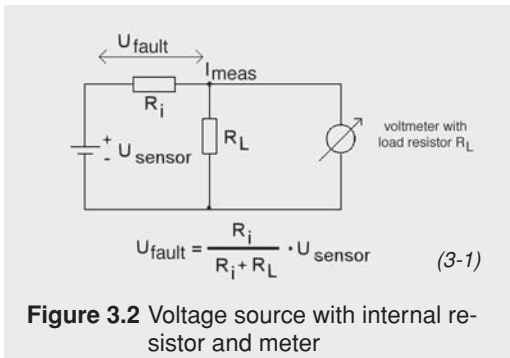
Figure 3.2 Voltage source with internal resistor and meter

Compensation measurement method

The compensation measurement method eliminates the above drawback with a controlled counter-e.m.f. which prevents current flowing between the sensor and the meter. Therefore the counter-e.m.f. equals the sensor's signal voltage and can be processed further without loading the sensor.

Frequency conversion method

A further fundamental measurement method used by electrical sensors is to convert the measured physical or electrical variable into a frequency or time interval.

From this very wide field we will consider just one basic method through an example.

Frequency conversion by an oscillating circuit

Together with other electronic components the sensor forms an electric oscillating circuit, the frequency of which is affected by the sensor. In other words, the frequency serves as a vehicle for the measurement data. This oscillating circuit is used to control an electronic oscillator, whose signal is then processed further. If a vibrating quartz or surface wave transformer is used as the sensor, it will directly control the oscillator frequency with high precision (see Section 2.2.3.3).

Figure 3.3 Oscillator with measuring quartz
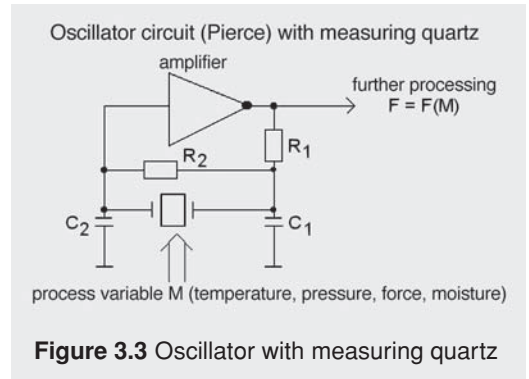
An electric oscillating circuit can also be formed with sensors that are capacitors or inductors. Electrical measurement signals produced by the frequency conversion method are particularly easy to transmit and process digitally.

The main difficulty associated with this method is due to the resistances of the supply lines to the sensor, since their compensation is limited. Separation of the sensor from the oscillator - a vital requirement for temperature measurements - is a critical exercise with limitations.

With voltage sensors and resistance sensors it is possible to influence the frequency of an oscillator (**v**oltage **c**ontrolled **o**scillator) via an active component, i.e. a transistor or diode. However in this case, allowance needs to be made for additional measurement uncertainties since the mea-

suring chain is extended by yet another conversion step.

3.1.1.2 Basic functions of transducers

The main function of a measuring transducer is to transform the individual sensor signal into a standardized signal suitable for transmission. This involves the signal passing through several processing and converting steps.

- Picking up the measurement signal from the sensor or generating it via the sensor. Thermocouple voltage can be picked up. For Pt100 sensors or piezo pressure sensors it has to be generated.

- Amplifying the measurement signal. This is essential because the further processing of such small voltages with sufficient accuracy is not possible, neither technically nor economically.

- Evaluating the measurement signal in relation to one or several standards. The signal has to be compared with a reference value for the further processing. A statement such as "the measured value is 0.25 V" means that the measured value is considered relative to the standard "1 volt". Generally, a "standardized" component or a "reference" component is used in metrology as reference value. A very simple rule applies for these cases: You can only compare like with like, i.e. voltage with voltage, resistance with resistance, etc.

In other words, conversion is only possible in relation to a reference standard. Where no such standard is directly available, it is created by superimposition of several standards. In this case, the drifts and errors of all the standards are input in the measurement.

This can be illustrated by the example of a Pt100 resistor measurement. A constant current produces a voltage drop at the resistor. The constant current is the first standard. The voltage at the resistor is measured relative to a reference voltage, i.e. the reference voltage forms the second standard. The reference voltage divided by the constant measuring current yields - in formal terms - the reference resistance for the measurement of the Pt100 resistor.

- Linearizing/equalizing the measurement signal. As a rule, the mathematical relationship between the process variable such as pressure or temperature and the sensor signal is non-linear. A linear relationship between the process variable and its representation by a standardized signal is generally required. This "linearization" or "equalization" is done in this conversion step.

- Converting the linearized measurement signal into a standardized output value. With the measurement signal in this form it can be reliably transmitted.

A number of additional requirements have to be met for this conversion chain to function with sufficient reliability and accuracy in practice. Unfortunately these requirements are not uniformly defined by standards for all transducers.

A number of supplementary standards exist in addition to the general VDI/VDE standards and laws concerning electrical equipment. Table 3.1 shows a selection of the most important test standards for transducers (see also Standards in the appendix).

Requirements are based on insensitivity to external interference such as:

- Ambient temperature, generally 32°F to 160°F (0°C to 70°C) in the control center, -40°F to 185°F (-40°C to 85°C) in the field.

- Change of ambient pressure, be it atmospheric pressure, gas pressure or water pressure in underwater applications.

Test and environment standards for transducers (pressure and temperature)	Contents of the standard
DIN IEC 770	General, summary standard for transducers, methods of assessing the performance of transducers
DIN 16068	Electric pressure measuring instruments, pressure sensors, pressure transducers, concepts, specifications in data sheets
DIN IEC 68-2 Part 1, 2, 3, 4, 6, 14, 31	Fundamental environment tests
IEC 160	Standard Atmospheric Conditions for Test Purposes

Table 3.1 Standards for transducers

- Ambient moisture. Occasional or continual condensation may occur from case to case.

- Aggressive surroundings such as sulphurous or ammonia air, acid vapors and other corrosive agents.

- Electromagnetic interference of all types (see Section 3.3).

Special operating conditions and requirements vary from case to case and must be considered separately at the development stage:

- Electrical separation of input from output in order to prevent ground loops and hum or when the measured medium is under voltage to ground.

- Operation in potentially explosive areas (see Section 3.4).
- Usage under high voltages or strong electrostatic fields near the transducer. Flashover and measuring errors can arise as the result.

- Occurrence of strong, erratically varying currents and magnetic fields near the transducer. The currents induced by these currents and magnetic fields cause measuring errors and may destroy the transducer. Even direct currents induce interfering currents at the moment they are switched on or off.

- Nuclear radiation at the point of use, i.e. in a nuclear power station. Radiation causes severe aging and decay in many materials.

The above mentioned environmental conditions may result in failures or premature failure of the transducer and sensor. A transducer must be designed to perform check functions in relation to failures in order to be able to respond to such failures, or it must be adequately protected against these failures by virtue of its design.

- External failures are:
  - sensor failures such as probe fracture, probe short-circuiting, sensor line fracture
  - power supply failures such as too low a supply voltage

- Internal failures are:
  - hardware defects such as a cold soldered joint, a hairline crack or component failure
  - firmware failures, i.e. internal, indelible programs or data in the processor are faulty
  - software failures, i.e. programs or data in the processor that can be changed from the outside are faulty

Today, firmware and software failures already account for more than 30% of the total failures of transducers. They should therefore not be underestimated as a risk factor.

A distinction is drawn between analog and digital transducers. These groups are not exactly defined, however, and the dividing lines are becoming increasingly blurred in technological terms.

3.1.1.3 Analog transmitter or transducer

An **analog transmitter** in the sense used here is a transducer which converts the signal without a processor or comparable digital circuit. The measurement data always directly exists in physical analog form - be it as voltage, current or frequency - and is not represented by logic states or digitized for further processing. Seen in these terms, a limit monitor that processes the measured value via operation amplifiers and than actuates a relay via a comparator is also an "analog" transmitter, even though its output signal has only digital states.

Analog transmitters are a far older development than digital transmitters. A "classical" analog transmitter can be illustrated by the following block diagram:

N L C = network, linearization, compensation
V = amplifier

Figure 3.4 Block diagram of an analog transmitter

Figure 3.5 Analog pressure and temperature transmitters
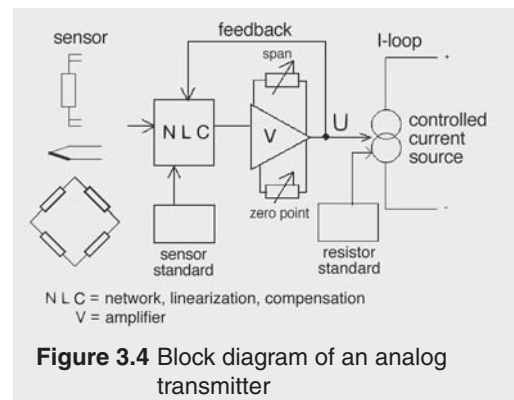
Analog transmitters have a number of fundamental advantages and disadvantages compared with digital transmitters.

The advantages of analog transmitters are:

- low production costs when low measuring precision is required
- fewer components are used in the circuit
- tested standard components can be used

- "soft response" to interference, i.e. the resulting error is generally proportional to the interference

- use of tried-and-proven technology; component characteristics, drifts and failure patterns are well known

• low energy consumption cuts costs and re-
duces component aging.

The disadvantages and risks of analog transmit-
ters are:

• high tolerance demands or more complex
functions mean high costs
  - component costs increase by a multiple
    when tolerances are closer
  - electrical separation and the linearization of
    thermocouples are very elaborate for
    purely analog systems

• adaptation to individual measurement condi-
tions is elaborate and lacks flexibility
  - adaptation of the measuring range requires
    complete re-calibration or a new transmitter

• internal check options are limited, and only
inflexible responses are possible

• only limited corrections are possible in relation
to external interference such as temperature

• additional data such as measurement history or
maintenance intervals cannot be verified inter-
nally

3.1.1.4 Digital transmitter or transducer

Digital transmitters in the sense used here are
transducers which digitize the measurement sig-
nal in the conversion chain. Logic states and num-
bers represent the measurement data. Further
processing is performed mostly in the micropro-
cessor on the basis of mathematical information,
not with physical analog representations. The
mathematical representation includes the physi-
cal relationships between the measured variables.
As the final step the value is converted into an
analog output signal, i.e. on the current loop from
4 to 20 mA. Such a transducer looks hardly any
different from an analog transducer, but what is
important is the internal representation and pro-
cessing of the measurement signal. Digital trans-
ducers have a digital interface for communication

with a PC, which is used for the internal calibra-
tion and parameterization of the transducer.

Conversion of the analog measurement signal
into digital data and vice versa can take place by
various methods. Some of the most important are
described briefly below.

Frequency analog-digital conversion

As explained in Section 3.1.1.1, the measurement
signal controls an oscillator, the frequency of
which is an analog representation of the measure-
ment signal as a function of time. An exact
counter, whose internal pulse represents the con-
version standard, digitizes the frequency, and the
measurement value is further processed as a
number.
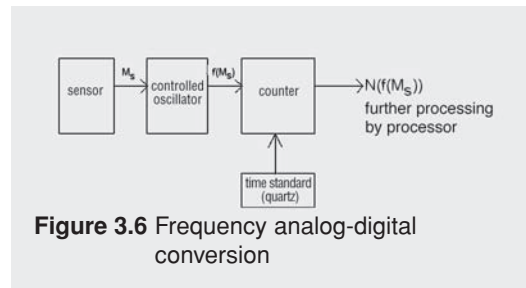
Figure 3.6 Frequency analog-digital
conversion

The advantages of the frequency conversion
method are listed below.

- The measured physical variable acts directly
  on the frequency-influencing component; There-
  fore pre-amplification of the measurement signal
  is not necessary.
- A frequency can be determined very precisely
  and effectively; the electrical signals can be fur-
  ther processed easily and without error.
- Dynamic adaptation of the resolution is possi-
  ble to suit the required accuracy.
- Electrical separation of input and output is very
  easy to achieve.

The disadvantages of the frequency conversion method are listed below.

- For temperature measurements it has to be possible to separate the frequency-defining sensor element from the rest of the electronic system. This leads to technical design problems and restrictions on sensor lengths and fields of application.
- If the frequency is generated after pre-amplification with a voltage-controlled oscillator (VCO), the oscillation drifts form an additional source of error.
- Components with a reproducible, non-individual frequency characteristic such as quartz are often subject to limitations of design and measuring range.

Parallel analog-digital conversion

With this method of conversion the measurement signal is compared simultaneously with a grid of reference voltages whose mutual spacing ΔU is constant. The highest reference voltage $N_1 \cdot \Delta U$ which is just smaller than the measurement signal is then the measure N_1 needed for the measurement signal. N reference voltages are required for a resolution in N steps.

The parallel method is very fast and particularly ideal for the scanning of high frequencies in the GHz range since the measurement reading is obtained in a single cycle step.

Unfortunately the method is very elaborate. N comparators and N reference voltages are required for a resolution of the measurement signal in N steps. Therefore today's customary resolution of 16 bits = 65534 steps requires 65534 comparators and reference voltages. Pre-amplification prior to the conversion is also needed for the measurement signals. Frequencies which are greater than half the cycle frequency have to be suppressed by an upstream filter to prevent aliasing effects. All components have to meet exacting tolerance requirements because imprecise com-

parator steps can result in counting errors.

Estimation analog-digital conversion

Among the estimation methods of conversion, also known as **iteration methods**, the best known in the "electronics world" are the **charge balance** or **switched capacity** methods.

The measurement signal is not converted in a single step but successively for each digit of the corresponding binary number, starting at the highest binary digit. If the measurement signal is bigger than the corresponding reference voltage for this digit, a "one" is set and the corresponding reference voltage is deducted from the measurement signal. If the measurement signal is smaller, nothing is changed, a "zero" is set and you move to the next smaller binary digit. Therefore a 12-bit resolution requires twelve steps for the conversion. With the charge balance conversion method, the signal is saved in a capacitor and the stored charge is compared with a reference voltage and a set of capacitors whose values correspond to the power of two series.

The advantages of the estimation methods are listed below.

- They are fast and inexpensive.
- They convert the measurement signal directly into a binary number.

Their disadvantages, on the other hand, are also listed.

- Components have to meet high tolerance requirements as otherwise counting errors are possible.
- A filter that suppresses frequencies greater than the cycle frequency divided by double the number of binary digits has to be installed upstream in order to suppress aliasing effects.
- Intermediate storage of the measurement signal in analog form is necessary.

Integrative analog-digital conversion

The best known of the **integrative methods**, also known as count methods, are the **dual slope** and **sigma-delta methods**. They involve counting how often the lowest reference voltage has to be added in order to obtain the measurement signal. The number of additions is the result. For 16-bit resolution the highest number is 65534. Therefore up to 65534 additions have to be carried out in order to obtain the measurement reading.

The advantages of the integrative methods are listed below.
- Counting errors are eliminated, allowing very high resolutions of up to 24 bits.
- Little circuitry and very little power are required to implement the methods.
- It is easy to change the resolution; methods which convert the measurement signal into a time measurement are particularly attractive.

Their disadvantages are also listed.
- Only small frequencies (up to approximately 100 kHz) can be converted; with high resolutions the limit frequency is far lower (approximately 1 kHz to 10 kHz).
- An analog pre-amplifier is required.

The dual-slope method:
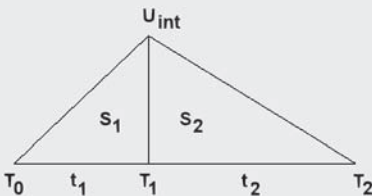
Figure 3.7 Dual slope method

With this method, a capacitor is charged for a fixed time period t_1 (integration phase) with a current I_1 that is proportional to the applied measuring voltage U_{meas}. If the measuring voltage is constant in this period, the capacitor voltage forms a curve as a function of time.
The slope S_1 of U_{int} in the integration phase is

$$S_1 = I_1 \cdot C = a \cdot U_{meas} \cdot C \qquad (3\text{-}2)$$
$$a = \text{constant}$$

At time T_1, U_{int} has the value

$$U_{int}(T_1) = t_1 \cdot S_1 \qquad (3\text{-}3)$$

From the time T_1 the capacitor is discharged with a constant current I_2, which is proportional to the reference voltage $U_{reference}$, the capacitor voltage forms a curve as a function of time.

$$S_2 = I_2 \cdot C = a \cdot U_{reference} \cdot C \qquad (3\text{-}4)$$

At time T_2 after period t_2 the capacitor is discharged again.
According to the radiation law:

$$\frac{t_1}{t_2} = \frac{S_2}{S_1} = \frac{a \cdot U_{reference} \cdot C}{a \cdot U_{meas} \cdot C} = \frac{U_{reference}}{U_{meas}} \qquad (3\text{-}5)$$

Equation (3-5) resolved to U_{meas} results in:

$$U_{meas} = \frac{t_2}{t_1} \cdot U_{reference} \qquad (3\text{-}6)$$

Since $U_{reference}$ and t_1 are fixed values, the time t_2 is a measure of the measuring voltage U_{meas}. Measuring the time t_2 with a digital counter or processor produces a digital value for the measuring voltage which is then further processed. It is interesting to note that the absolute value of the capacitor is itself insignificant. The only condition is that the system works linearly.

Sigma - Delta ADC

Figure 3.8 Sigma-delta method
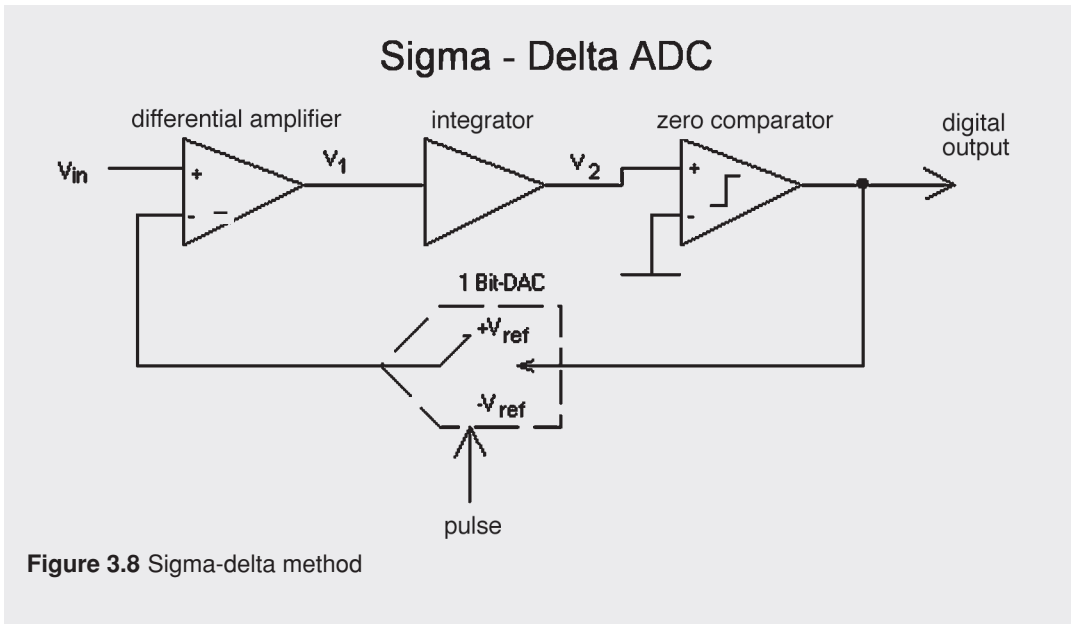
The advantages of the dual slope method are listed below.

- The digital resolution of the measurement value can be changed within wide limits without any great effort.
- A filter for 50/60Hz hum and multiples of these frequencies can be produced as integration methods.
- Value aging and temperature drift of the integration capacitor has no effect on accuracy.
- Time measurements are particularly accurate and easy to take.

The disadvantages of the dual slope method are also listed.

- Only low conversion rates of up to 100/s are possible for a resolution of more than 16 bits.
- The integration capacitor requires a relatively large capacitance; it cannot be integrated on a chip during production.

The sigma-delta method:

With the sigma-delta method the difference between the input signal and the output voltage (V_{in} - $+V_{ref}$) is amplified. The 1-bit analog converter can only accept the output values $+ V_{ref}$ or $- V_{ref}$. From the beginning let us assume we have $+ V_{ref}$ at the output of the 1-bit digit-analog converter and V_{in} is smaller than $+ V_{ref}$. The following integrator deintegrates because V_1 is smaller than 0 V. The downstream comparator sets a "one" at the digital output until V_2 becomes smaller than 0 V and a "zero" is set at the digital output. At the next pulse the 1-bit DAC switches to $- V_{ref}$. V_1 becomes bigger than 0 V and the integrator now integrates in positive direction until V_2 becomes bigger than 0 V again. The whole process than re-starts from the beginning which results in a series of zeros and ones at the digital output. Superimposition of the asynchronous zero crossings of the integrator with the pulse cycle applied from the outside produces a periodic chain of zeros and ones. The period duration for each input signal is individual. The ratio of the number of zeros and ones in one

period represents the ratio of the measurement signal to the reference voltage. In mathematical terms:

N_0 = number of "zeros"
N_1 = number of "ones"

The following applies for at least one or several periods with a total of $N_0 + N_1$ pulses:

$$\frac{N_1}{N_0 + N_1} = \frac{V_{in}}{2 \cdot V_{ref}} + 0.5 \qquad (3\text{-}7)$$

The advantages of the sigma-delta method are listed below.
- Integration of the circuit is very straightforward.
- The method can be implemented with little expense.
- Higher-order digital filters can be integrated as well.
- The resolution can be changed dynamically.
- The application range extends to around 100 kHz.

The disadvantages of the sigma-delta method are also listed.
- The mathematical processing is elaborate; a higher-order digital filter has to be installed up-stream, making the transient response more complex than in the parallel method or dual slope method.
- A filter that suppresses frequencies bigger than half the pulse frequency must be installed downstream in order to prevent aliasing effects.

All these methods of conversion face the same basic problems.

- They require an aliasing filter (except for the dual slope method).
- They need pre-amplification (except for direct frequency conversion).
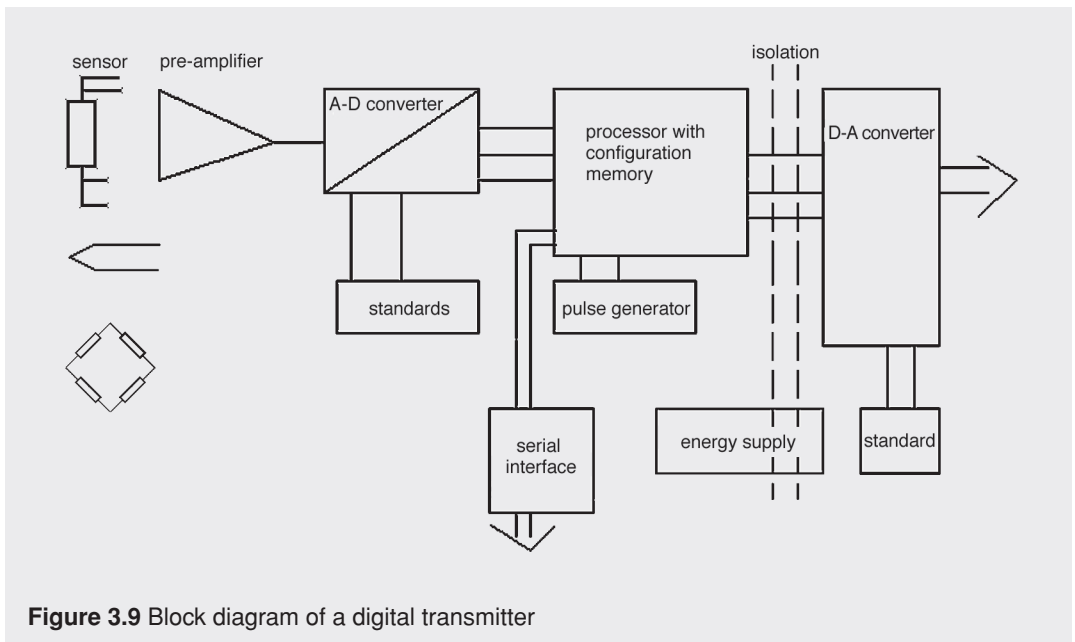
Figure 3.9 Block diagram of a digital transmitter

Figure 3.10 Sectional view of a digital temperature transmitter (WIKA)
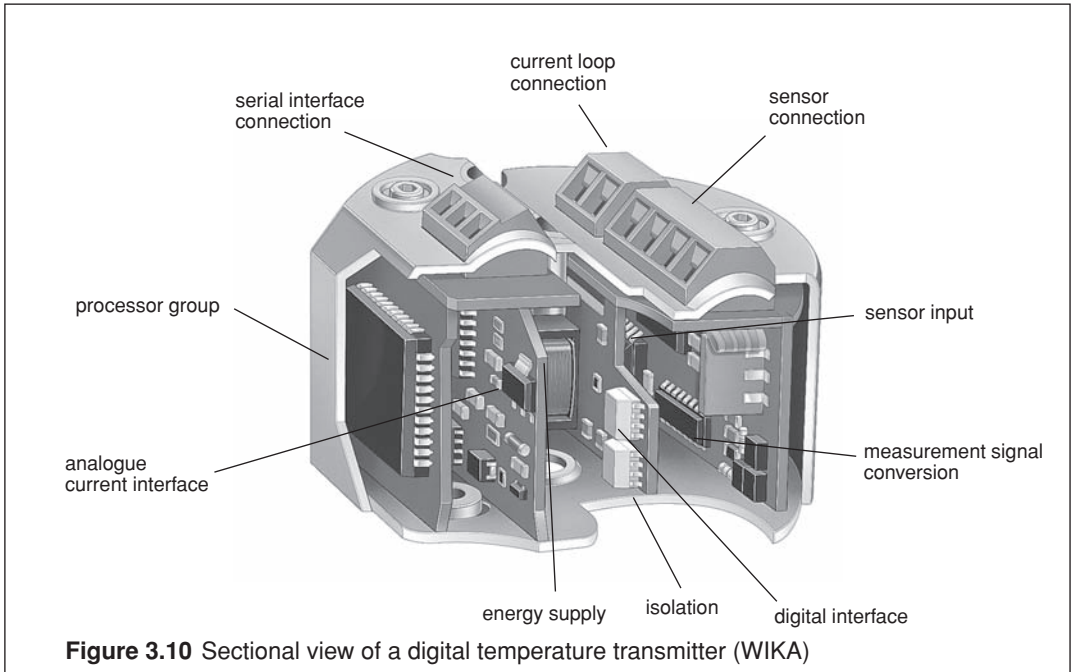
Design of a digital transmitter

Figure 3.10 shows the fundamental structure of a digital transmitter with current loop output.

Figure 3.9 shows how the functional blocks of a digital transmitter are interconnected. Here the digital interface is mainly for configuration purposes, but it can also be used for direct output of measured values to a PC or process control system.

In this example the output interface is designed as a current loop interface, but it could also be a digital output (relay or switch etc.).

The advantages of digital transducers are listed below.

- For high tolerance requirements they cost less than analog instruments.
- Flexible adaptation to specific measuring conditions such as measurement range, sensor etc. is possible.
- There are good possibilities for making inter-

nal corrections in the event of external interference; drifts due to ambient temperature, EMC or other physical effects can be compensated by follow-up mathematical correction and filtering functions.
- A high level of self-control is possible via the processor by integrated check functions.
- Additional data (maintenance, history etc.) can be verified internally.
- Linearization and processing of even complex characteristic curves are possible without difficulty.
- Complex interlinking of different sensors (externally and internally measured) is possible.
- Error-tolerant and interference-proof signal processing after the conversion.

The disadvantages of digital transducers are also listed.

- High cost of components even for low requirements on tolerance; basic expense is greater than for a simple analog transducer.

- Digital transducers are a relatively new technology. Therefore the long-term stability of specific components such as EEPROMs and processors is still uncertain or critical under high ambient loads and has to be carefully tested.
- "Hard response" to high interference levels, i.e. if a digital transducer is disturbed above its safety threshold, it is not possible for the error to be limited to a percentage range but every potential output value between the minimum and maximum value may arise.
- Digital transducers have a higher energy requirement than analog transmitters; new technologies are making this point less and less significant.

3.1.2 Standardized analog signal transmission

A number of standard analog interfaces have developed as a result of the various areas of application in industry (laboratory, control centers, process fields) and the state of technology at the respective time of introduction (see also Section 1.5.1.2). These standard analog interfaces can be classified in two groups according to the mode of transmission.

3.1.2.1 Voltage transmission

With **voltage transmission** the measured value is output as a voltage signal. The minimum value of the range (also known as the start of scale) is usually linked with 0 V as the smallest output value. The maximum value of the range (also referred to as full scale) is linked with the maximum output voltage value. Intermediate values are represented in linear relationship to these boundary values. In rare cases the relationship is not linear but the square or the square root. Square or square root representations are used most often in flow technology.

For example, given a measuring range of 0 bar to 10 bar and an output signal of 0 V to 10 V, 5.5. bar is output as 5.5 V.

$$U_{Output} (p) = \frac{10\ V}{10\ bar} \cdot p \qquad (3\text{-}8)$$

$$U_{Output} (5.5\ bar) = 5.5\ V$$

The most commonly used standard voltage interfaces are 0V to 10V, 0V to 5V, 1V to 5V, and -10V to 10 V.
The use of these interfaces is limited to internal interfaces, the laboratory, and control cabinets in control centers because these interfaces are not very resistant to interference. Transmission over long distances (200 ft. to one mile) is highly vulnerable.

A fault signal such as probe fracture or internal hardware failure is difficult to separate from the normal measurement signal. The signal 0 V is an alarm signal only for 1 V to 5 V.
Transmission of -10 V to 10 V is intended to allow signed physical variables such as differential pressure to be represented in correct relationship to zero.

3.1.2.2 Current signal transmission

Over the past 20 years the current loop has become established in the process field as the standard for analog measurement transmission over long distances.
So-called 4-wire and 3-wire transducers use currents for representing the measured value from 0 mA to 20 mA or 4 mA to 20 mA. The 2-wire transducers use only currents from 4 mA to 20 mA. The current loop 4 mA to 20 mA is also known as **live zero**.

Like the voltage transmission system, the smallest value of the measuring range is allocated a current of 0 mA or 4 mA and the highest value of the range is assigned a current of 20 mA. Measured values between the start of the scale and the full scale value are represented in linear relationship to the boundary values.

With 2-wire transducers, on the other hand, the transmitter controls the current on the loop "passively", i.e. without its own power supply. The electrical power supply needed is taken from the current loop. This means that a current of only 4 mA to 20 mA is possible with 2-wire transducers.
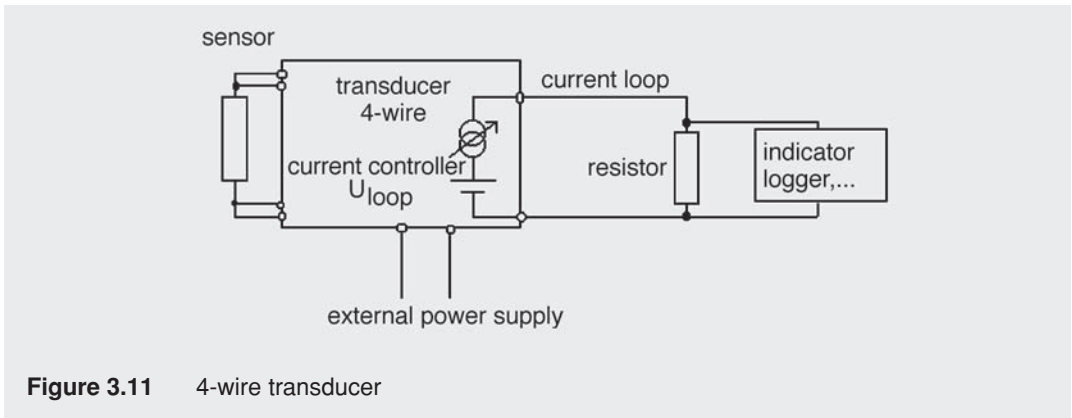
Figure 3.11   4-wire transducer

The name 4-wire or 3-wire transducer means that these transducers have a separate power supply and actively output the current on the loop. This technology is often used for transducers mounted on a top-hat rail and for 19" plug-in transducers because the power supply is already available in the control center.

The advantages of the 2-wire transducer are listed below.

- Up to two cable routes are saved, which in large process systems is a notable advantage; therefore 2-wire transducers are often less costly than installing a 3-conductor PT100 resistor in the control room.
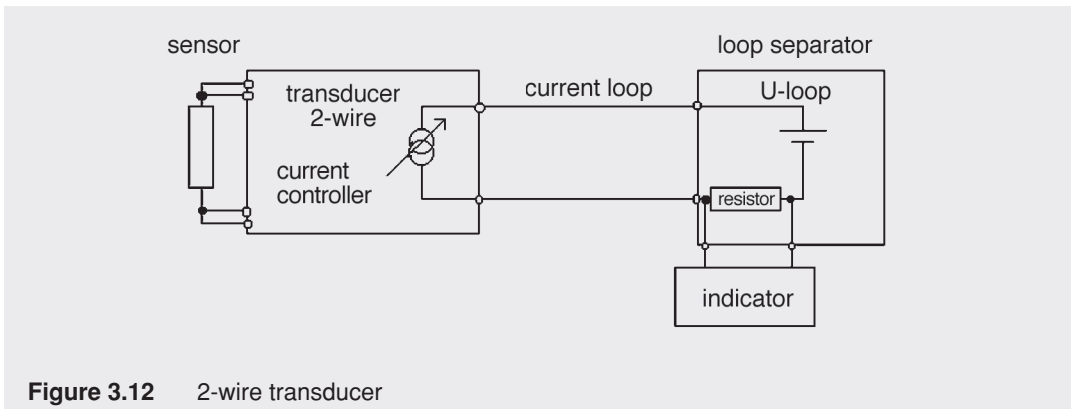
Figure 3.12   2-wire transducer

- When a 2-wire transducer is used in potentially explosive systems, there is no need for the elaborate installation of an additional Ex-protected power supply.

In current loop signals, faults are represented by **limit values** (Table 3.2).

Supply units or **supply separators** are used to supply the current loops. They are available in many different versions. Depending on the application they perform electrical separation and/or isolation of the explosion-protected area from the safe area (see Section 3.4.1.3). The most widespread design types are units for rail mounting or 19" plug-in units.

The advantages of current loops are listed below:

- They are economical to use; the modules, transducers and supply separators are widely used and therefore economically priced.

- They are resistant to interference and therefore well suited for long-distance transmission.
- Fast simultaneous transmission of the measured value is possible.
- They have a wide field of application because they can also be used in potentially explosive areas.

The disadvantages of current loops are listed.

- Only star circuitry or one-to-one wiring is possible; installation costs for the wiring are therefore moderately high.
- It is not possible to transmit differentiated fault signals from the transducer or maintenance signals from the process control system to the transducer.

Meaning	0 mA to 20 mA - **current loop**	4 mA to 20 mA - **current loop**	Notes
Lower limit value, controlling closed	0 mA	≤ 3.6 mA	
Intermediate range, undefined, or range overflow	___	> 3.6 mA to $\leq 3,8$ mA	Recommendation NAMUR NR 43 for transducers
Range overflow and adjustment range	___	> 3.8 mA to < 4.0 mA	Recommendation NAMUR NR 43 for transducers
Measured value	> 0 mA to $\leq$ 20mA	≥ 4.0 mA to ≤ 20 mA	Standardized signal range acc. to DIN 381, Part 2
Range overflow and adjustment range	> 20 mA to ≤ 20.5 mA	> 20 mA to ≤ 20.5 mA	Recommendation NAMUR NR 43 for transducers
Intermediate range, undefined, or range overflow	> 20.5 mA to < 21 mA	> 20.5 mA to < 21 mA	Recommendation NAMUR NR 43 for transducers
Upper limit value controlling open	≥ 21.0 mA	≥ 21.0 mA	
Table 3.2 Meaning of current loop signals			

3.1.3 Digital signal transmission

3.1.3.1 Standardized electrical digital interfaces

Various standard interfaces, many of them originally developed for other purposes, have become established for different cases of application in computer-aided measurement systems. Basically these interfaces can be classified as serial or parallel interfaces according to their mode of data transmission.

Serial interfaces

Serial interfaces transmit **data words** (called **bytes**) one bit at a time. A **bit** is the smallest transmittable unit of data and can have only the value "zero" or "one". The receiver has to reassemble the arriving bits into whole bytes or words. One byte consists of 8 bits. Interfaces differ in their physical definition of electric level and time.

V.24/RS232C interface

The interface **V.24/RS232C** is defined in the US standard RS232C. The RS232C interface is a voltage-based one-to-one connection of 2 devices. Between 3 and 21 lines are used for communication in both directions, depending on the device. The first device is the computer or **d**ata **t**erminal **e**quipment (DTE). The second device is referred to as the **peripheral** device. This peripheral device can be a DTE (a computer etc.) or **d**ata **c**ommunication **e**quipment (DCE). A **modem**, for example, is a DCE.

Two data lines are used for the **d**ata **c**ommunication: the transmit data (TxD) and **r**eceive **d**ata (RxD) lines. Control and **signal lines** are defined for coordination between the participants and can be used individually according to the manufacturer. The electrical levels are shown in the following table.

Line type	Level +3V to +15V	Level -3V to -15V
Data line	Logic zero	Logic one, idle state
Control line	On	Off
Signal line	On	Off

Table 3.3 Electrical levels of RS232C

Logic assignment is not defined for other voltage levels outside -15 to -3V and +3V to + 15V.
A standard data transmission speed of 300, 600, 1200, 2400, 4800, 9600 and 19200 baud (1 baud = 1 bit/s) can be used for PCs.
The RS232C interface is used above all as an economical PC interface for printers, modems, fax machines and measuring instruments. It can only be used, however, for a maximum length of 20 feet and cannot be used in conditions of high electromagnetic interference.

RS485 interface

The disadvantages of the RS232C interface, particularly its lack of immunity to interference and restriction to 2 devices, led to the development of the **RS485 interface**. This interface is able to transmit the same serial data protocol as the RS232C interface, but it is physically defined to allow a maximum of 32 standard devices to be connected together. With the RS232C interface, fixed voltage levels are defined in relation to earth. With the RS485 interface, on the other hand, a signal voltage VA-VB is fixed between two conductors A and B with an amount $|VA-VB| \geq 0.3$ V. The absolute level to earth can vary greatly; what is important is the voltage difference.
The conductors A and B must be terminated by resistors in order to prevent reflections during signal transmission. Here the signal status definition is as given in Table 3.4.

Line type	VA - VB ≥ +0.3V	VA - VB ≤ -0.3V
Data line	Logic zero	Logic one, idle state
Control line	On	Off
Signal line	On	Off

Table 3.4 Electrical levels of RS485

Greater immunity to interference as well as high baud rates over long distances of at least 1000 feet and often as far as 1500 feet can be achieved with this interface. Most of the more recent field bus developments (see Table 3.8) are therefore based on this interface definition.

IEC standard for Ex version of the RS485 interface

By virtue of its basic definition, the RS485 interface is not suitable for applications in potentially explosive areas because of the possibility of excessively high currents and ignition energies. This prompted the development of a modified form of the RS485, which is defined in the standard IEC/ISA-SP50.

A common feature of this modification and the basic RS485 is the concept of signal transmission by reversing the polarity of two conductors, i.e. alternating voltage transmission. In this case the static state of the line is no longer the data carrier, rather the direction of polarity reversal. This method is also referred to as edge transmission.

Edge sequence	Meaning
First rising, then falling edge	Logic one
First falling, then rising edge	Logic zero

Table 3.5 Edge transmission

The advantage of this method is that the current flow is minimal, which means that on average very little power needs to be provided. This is a necessary condition for use in potentially explosive areas.

Audio frequency transmission

With the existence of telephone networks it is possible to transmit measurement data over phone lines. Transmission over telephone networks is restricted, however, to frequencies from 300 Hz to 3000 Hz, which corresponds to the frequency range of human speech. It is necessary, therefore, to convert the logic significance of zero and one into audio frequency codes.

Graphic data and general computer data is encoded in audio frequencies and transmitted by fax machine and modem respectively, while the received data is decoded. This process is based on specifications 202S and 202T of the Bell company.

SMART or HART® protocol

Audio frequency transmission is the basic idea behind the SMART or HART® protocol, an application of the widely available 4 mA to 20 mA current loop. This method is based likewise on the Bell company's specifications 202S and 202T. Further definitions can be found in the "HART-SMART Communications Protocol Specifications" from Rosemount Inc. The direct current of the current loop still represents the measured value; it is superimposed with audio frequencies of 1200 Hz and 2400 Hz, which are used for serial digital communication between the digital transducer and a PC or hand-held device. The maximum baud rate is limited to 2400 baud (bit/s). Fast transmission of measurement data is not possible, therefore, but the speed is high enough for the inspection and configuration of transducers and for servicing and maintenance purposes. A special advantage - but also a restriction - is to use the existing current loop wiring. Interface costs are comparatively high, however.

Extension of this approach into a simple field has given rise to the MULTI-DROP method. In this case the current loop forgoes its measurement signal transmission function and is used only for the power supply. A current of 4 mA is set at each transducer. Up to 15 participants operated by a master can be connected in parallel. In this arrangement the measured value must also be transmitted digitally, which for 15 participants means response times of around 1 s. This is usually sufficient for temperature measurements but unacceptable for pressure measurements.

In the long term the MULTI-DROP method and HART® protocol will be unable to survive the challenge of genuine field buses. The advantage of using existing conductor systems does not apply to new installations, and the higher interface costs are a negative factor.

Pulse interval modulation

With pulse interval modulation, a method that is technically related to frequency transmission, the measured value is represented by the time interval between two current pulses or voltage pulses. The receiver measures the time between the pulses and calculates the measured value on this basis. The mathematical relationship between measured value (process variable) and interval time can be linear, as with the voltage and current interfaces. In other cases, like with quartz temperature sensors, the frequency of the sensor is represented directly by the pulse interval. With this arrangement the receiver has to make allowance for the non-linear relationship between frequency and process variable. This method is particularly useful for frequency-converting sensors, such as temperature-dependent quartz or surface wave converters. By interweaving the individual pulses it is possible to transmit several measured values economically even at high resolution. The ILTIS bus works on this basis.

The advantages of pulse interval modulation are:
- Interference-proof transmission by current pulses over large distances.

- With frequency-converting sensors, the measured value resolution is determined by the time-related resolution of the receiver.
- Simple wiring (twisted-pair) is usually sufficient.
- The method is bus-compatible.
- Mixing with serial digital data communication is possible; the METER bus is an example.

One disadvantage of pulse interval modulation is that it is still not possible to get high rates of measured data and high accuracy at the same time.

Digital parallel interfaces

Unlike serial interfaces, digital parallel interfaces transmit at least one or two complete bytes, i.e. 8 or 16 bits, simultaneously in parallel over the corresponding number of data lines. Additional lines are required for signal and control purposes.

Parallel interfaces allow a faster exchange of data than serial interfaces. Parallel operation of several devices can be engineered at low cost.

Unfortunately, the installation and wiring expense is greater than for serial interfaces because of the numerous lines.

The Centronics interface

The Centronics interface is the most widely used printer interface on personal computers. It is not standardized but has established itself as a standard. It is also used to a limited extent for the transmission of measurement data.

Voltage levels (TTL) of 0V and 5V, both positive and negative logic, are used.

Line type	0 V to 0.8 V	2.0 V to 5 V
Data line	Logic zero	Logic one
Control line	Off	ON
Signal line	Off	ON

Table 3.6 Level definition (positive logic)

With the Centronics interface widely used as a computer interface and using the standard level TTL, it is priced very economically.

Its low electromagnetic compatibility (EMC) means, however, that maximum line lengths of only 10 feet are possible. The Centronics interface is used exclusively in the laboratory; it is unsuitable for process field applications.

The IEEE 488.2 interface

The **IEEE 488.2** interface holds a special status among parallel interfaces. It is also known under the names HP-IB, GP-IB, IEC 625 and ANSI MC 1.1. Since its first appearance in 1965 it has become a firm standard for the linking devices in the measurement laboratory. Up to 14 devices (talkers and/or listeners) can be connected in parallel, with a master controlling the communication.

TTL voltage level technology (see above) is also used here.

As with the Centronics interface, IEEE 488.2 is a widely established standard in laboratory equipment. Parallel transmission allows a high data transmission rate of up to 1.2 Mbaud. Poor immunity to interference means that the maximum line length between devices is about 20 feet (extending to 60 feet in special cases), which although sufficient for the laboratory is problematic in the process field.

3.1.3.2 Field bus systems

A great deal has been said and written about field buses over the past seven years. A field bus is a communication system that can be used for communication, measurement and control purposes in industrial processes.

The advantages of a field bus are considered to be as follows.
- It allows a higher density of data than is otherwise possible; this is a vital condition for the linking of industrial production processes.
- A field bus allows greater flexibility in production.
- Communication by computer is possible - across all control levels.
- A higher level of measurement and transmission precision is possible than with analog technology.
- Simple and fast computer-based storage of data is possible.
- Low-cost planning, installation and assembly.
- Self-diagnosis capabilities mean that field bus systems require less service effort for fault diagnosis and the repair of breakdowns.

Reference model OSI (Open System Interconnection)

The **O**pen **S**ystem **I**nterconnection (OSI) **reference model** was developed by the **I**nternational **S**tandards **O**rganization (ISO) to serve as a standard for allowing compatibility between various

7	User layer	higher protocol-layers	User interface, user program
6	Presentation layer		Computer-independent presentation and conversion of data
5	Synchronization layer		Synchronization of functions and checking of authorizations, connections
4	Transport layer		Conversion of addresses and paths, physical address definition
3	Network layer		Connection rules and structure for communication between networks
2	Data protocol layer	transmission	Data security functions, transmission error detection for a data packet
1	Physical layer	protocol layers	Physical definition of the connection (electric level, plug, mechanics)

Table 3.7 OSI model of protocol layers

devices, interfaces and manufacturers. For this purpose, the communication system is hierarchically structured in seven "protocol layers" (Table 3.7).

There are interfaces between the adjacent layers. During send mode, the data is passed by the user layer through to the lowest layer, the various layers changing or extending the send data in a layer-specific manner. Finally, the physical layer establishes the connection to the physical layer of the receiver. Layer-specific restoration of the data then takes place in the receiver. With the data simply being exchanged between adjacent layers, it is possible for the layers to be defined largely independently of each other.

There is no need for field bus systems to fill all the layers of the OSI model. The more layers there are, the more universal but also the more complex and time-consuming the bus. Various demands are placed on the bus according to the application. Metal machining requires **bus response times** as a **real-time condition**; in other cases, i.e. hydrological field measurements, response times in the minute range are sufficient. Table 3.8 provides an overview of various field buses with their characteristic data and current fields of application.

3.1.4 Signal processing and evaluation

After the measurement signal has arrived in standardized form in the control center, it has to be displayed and further processed for the process control system, and it has to be stored for documentation purposes. Displaying the measurement signal for the human eye used to be vital because "man" would then control the process by direct intervention. Automatic response was restricted mainly to safety circuits and alarms. Today the systems are automatic. The measured value is evaluated by computer or the process control system and used accordingly to regulate the process. Displaying the measured value only serves as information. Human intervention in the control chain is only necessary in an emergency. The necessary requirements required by control center

equipment have changed accordingly.

3.1.4.1 Analog and digital indicators

Measured value indicators convert the measurement signal and present the measured value in optical form. They are designed as flush-mounting devices for wall panels, as bench-type devices (also known as stand-alone devices) and as cubicle-mounting devices. Measured value indicators are still the most important man/information interface in measurement systems.

Analog indicating systems

Analog indicators show the measured value in optical form with the help of a scale. In this case, analog means that a pointer or bar indicates the measured value on the scale continuously, i.e. without any jumps between points.

Examples include the dial indicators on pressure gauges, mechanical thermometers (see Section 1.4.3 and Section 2.6) and motor vehicle speedometers. Older engineers will also remember moving-coil instruments and galvanometers for indicating electrical values.

The advantages of analog indicators are:

- Fast high-quality readings, even from a distance.
- Clear recognition of trends, i.e. changes of value per unit of time.
- They are particularly useful as zero indicators.

The disadvantages of analog indicators are:

- They are subject to mechanical wear and aging.
- Mechanical inertia limits the response time with fast measurement signals.
- Mechanical hysteresis is an additional measurement uncertainty.
- Resolution is limited.

Table 3.8 Overview of the most important field buses

Field bus	phys. basis	layers in the OSI model	Response time	Transmission rate	Data suitability (preference)	Multi-master	Direct-network capability	Max. Length per segment / total length	Participant per bus segment/ total max.	Ex-proof version	Area of application, notes
DIN-measurement bus	RS 485	1, sometimes 2	3.4 ms	110 Baud to 1 MBaud	Measurement data	no	no	1650 ft. /	32/ 32	no	Plant engineering, automotive engineering, simple near-process applications
Bitbus	RS 485	1, 2, 7	>1 ms	62.5 kBaud to 2.4 MBaud to 500 kBaud	Measurement data binary	no	no	4000 ft./ 13,000 ft.	29 /250	no	Plant engineering, robots, near-process applications and process control systems
Interbus S	RS 485	1, 2	> 2 ms	9.6 kBaud to 2.5 MBaud	Measurement data	no	no	1300 ft. pro participants / max. 8 miles	256/ 256	yes, "Sensor-ASI"	Plant engineering, near process application
Profibus	RS 485	1, 2, 7	> 1 ms	9.6 kBaud to 2.5 MBaud	Measurement data, general data	yes	no	4000 ft./ 13,000 ft.	32/122	i.V.	Plant engineering, data acquisition, computer links, near-process applications and process control systems
ISP *(currently being changed to "World-FIP")*	RS 485	1, 2, 7	> 1 ms	9.6 kBaud to 1 MBaud	Measurement data, general data	yes	no	6000 ft./ 13,000 ft.	32/122	yes	Plant engineering, data acquisition, computer links, near-process applications and process control systems
CAN-Bus	RS 485	1, 2, 7	> 1ms	76.8 kBaud 32 kBaud to 1 MBaud	Measurement data	yes	yes	3000 ft./ 3000 ft.	32 knots/ unlimited (theoretically)	no	Plant engineering, robots, motor vehicles, applications with distributed intelligence, near-process applications, computer links
P-Net	RS 485	1, 2	2.8 ms	9.6 kBaud	Measurement data	yes	yes	4000 ft./ 16,000 ft.	32/125	i.V.	Plant engineering, near process application
FIP	RS 485	1, 2, 7	>1.5 ms	9.6 kBaud	Measurement data	yes	no	4000 ft./ 16,000 ft.	32/256	i.V.	Plant engineering, data acquisition, computer links, near-process applications and process control systems
ASI	2-wire,	1, sometimes 2	5 ms	9.6 kBaud	Binary	no	no	350 ft.	31 // 31	no	Exclusively digital sensors, lowest process level
Meter-Bus	24V-/pulses 2-wire/	1, 2	10 ms		Measurement data	no	no	3000 ft.	256	no	consumption meter lowest process level
EIB	current pulses 2-wire/ 24V	1, 2, 7	5 ms		Binary	no	yes	2000 ft.	64	no	Building services management systems

Digital loggers with a colored pen for recording the measurement signal as a function of time on continuous paper tape have long been used for the documentation of analog electric signals.

Loggers have the following advantages.
- Direct presentation and storage of process variables as a function of time.
- Trends can be identified very easily "at a glance" because the human eye is able to analyze curves very easily.

Their disadvantages are:
- Resolution is limited by time and signal technology.
- Loggers are sensitive to vibrations and environmental influences.

Loggers used to have a purely analog design and were considered precision mechanical products with high accuracy. The classical logger, however, has long since been superceded by digital technology. In general, today's loggers are computers with analog inputs and an integrated printer. The disadvantages listed above are compensated in part by storage technology, complex processing and additional displays.

Digital indicating systems

Digital indicators display the measured value using an alphanumeric representation. Alphanumeric means that only figures and letters are used.

Digital indicators have the following advantages.
- High resolution is possible according to the desired number of decimal places each individual case.
- They are very fast.
- Additional information, i.e. error messages or physical units, can be presented as well.
- They are economically priced and suffer no mechanical wear.
- They are flexible in use.

The disadvantages of digital indicators are:
- Measurement value trends are difficult to identify.
- They are not well suited to function as zero indicators.

Digital indicators are used for presenting loop current measurements (0 mA to 20 mA or 4 mA to 20 mA). As passive loop devices they draw their power from the 4 to 20 mA current loop. Active loop devices are supplied with external power. The digital indicator as a digital multimeter has completely replaced analog instruments in the laboratory. Some designs show not only the numerical measurement values but also present the measurement as a semi-analog bar or pointer display. This makes it easier to identify trends.
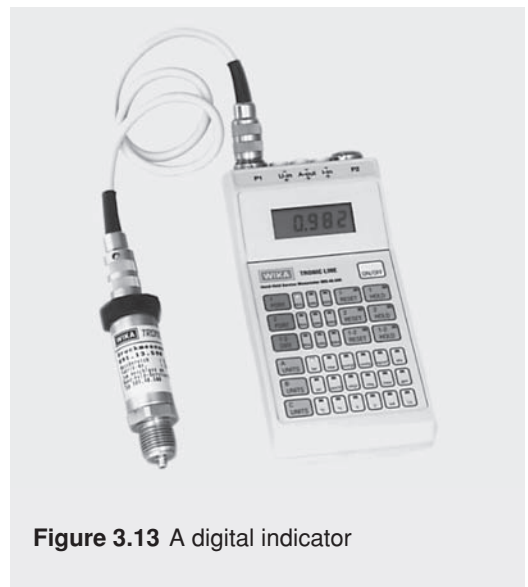
Figure 3.13 A digital indicator

The continuing proliferation of process control systems and PC-supported measuring systems is reducing the importance of indicators and loggers as separate devices. On the one hand they are being integrated as "windows" in the screen display, on the other hand their storage function is being taken over by the diskette.

3.1.4.2 Stored program controllers (SPC)

The **s**tored **p**rogram **c**ontroller (**SPC**), which dates back to the nineteen-seventies, is to process measuring technology what the numerical controller (NC) is to mechanical processing equipment. The method can also be compared with time dial controlled washing machine programs, except that an SPC is flexibly programmable. Various measurement signals from sensors - originally only digital, but now also analog - are linked logically/mathematically with digital output interfaces on an internal relay (bus) using a computer module. Inside the computer a numerically coded user program operates relay interfaces for actuators on a time cycle and logic-related basis, thereby controlling the manufacturing process. The "S5" is widely used in industry today. SPCs are used in production systems, on complex processing machines and in small chemical plants. The new generations now entering the market, i.e. the "S7", are able to perform far more complex control functions.
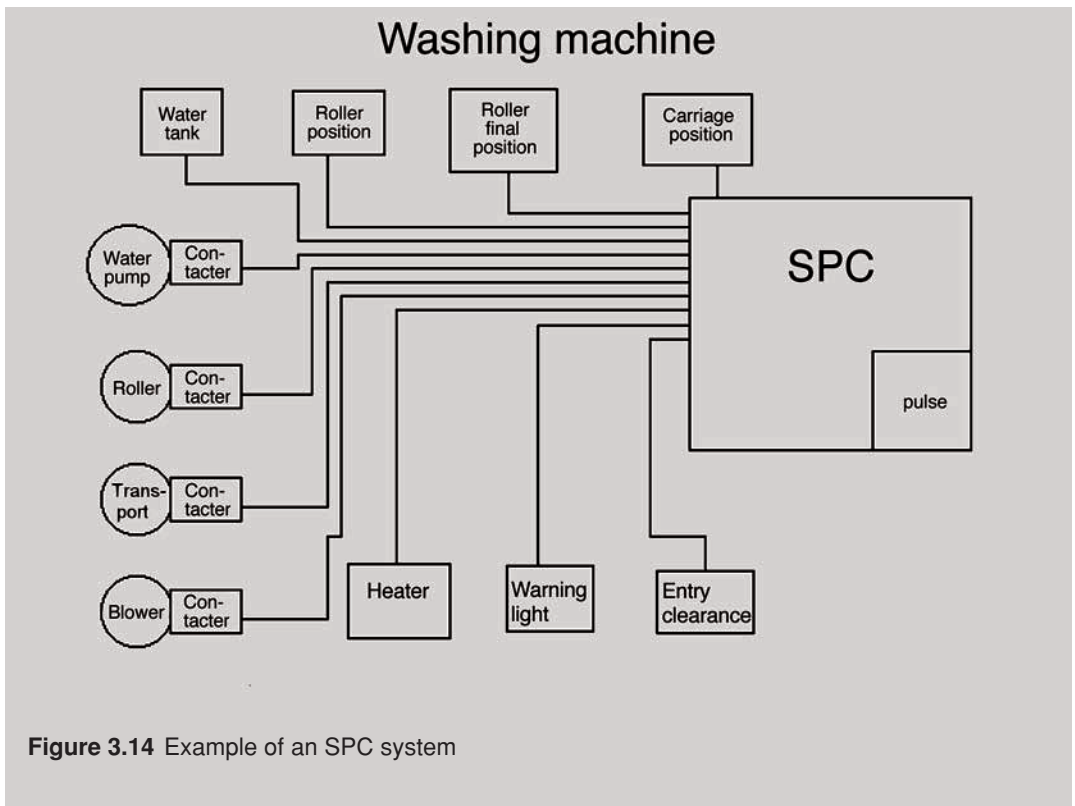
Figure 3.14 Example of an SPC system

Figure 3.15 Control loop
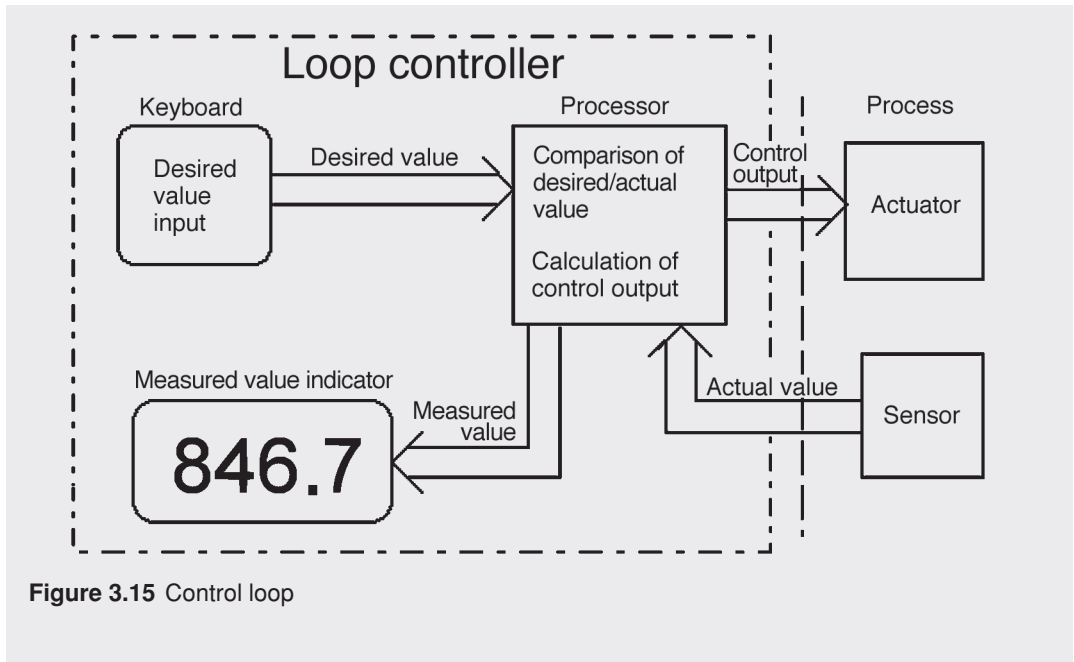
3.1.4.3 **Loop controllers**

Today's normal loop **controller** combines the entire measuring chain consisting of sensor input, signal processing, presentation, further processing and actuator control into a single device. An input interface for parameterization and preferred value input is also included. The loop controller represents the classical control loop of information theory in compact form (Figure 3.15).

Loop controllers are classified according to type of algorithm, i.e. their internal computing standard. A distinction is drawn between 2-point loop controllers, proportional loop controllers (P-controllers), proportional-integral controllers (PI-controllers), proportional-differential controllers (PD-controllers) and proportional-integral-differential controllers (PID-controllers). The latest development step to have established itself is **FUZZY technology**, which programs human experience of the production process into the loop controller in the

form of "rules of behavior". Fuzzy controllers are more stable and often more effective in their control performance than classical loop controllers.
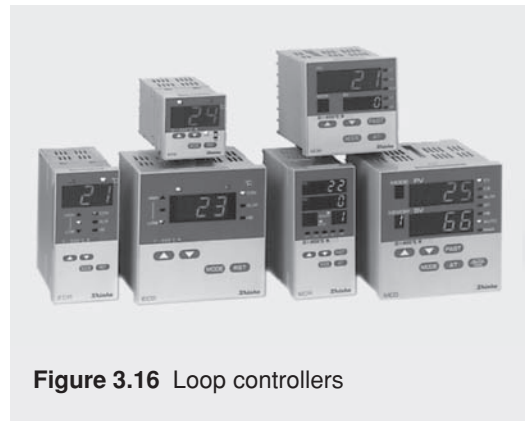
Figure 3.16 Loop controllers

3.1.4.4 Computer-aided evaluation

A process control system may require complex mathematical logic operations between sensor-measured values. Often the measuring process and production process need to be flexible for get the most efficient installation. In these cases, large installations are controlled by a process control system and laboratory-scale processes by a PC. The computer performs all the logic operations between the measured values, stores them, presents them in graphic form and controls the actuators in the process. In other words, it performs all loop control, logging and documentation functions.

The measured values can be gathered by computer via an IEEE bus in the laboratory or a field bus in the field. Documentation of device-specific parameters, maintenance history and service requirements are also carried out in the computer. With computers becoming increasingly universal, cheaper and more powerful, the classical loop controller and logger are likely to vanish almost completely.

The following diagram (Figure 3.17) represents a PC-aided installation with field bus for ammonia production as an example.
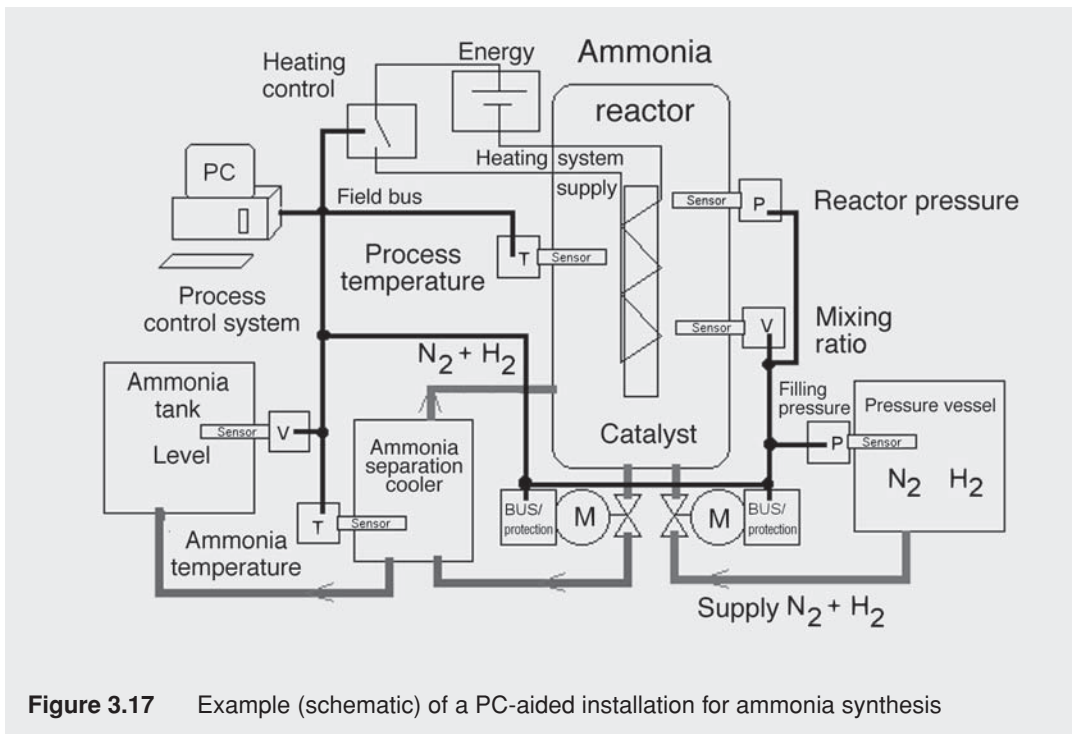
Figure 3.17   Example (schematic) of a PC-aided installation for ammonia synthesis

3.2 Calibration

Pressure and temperature as measured variables play an important role in industrial production processes. Product quality, operational safety and economy are almost always directly linked with accurate and reliable recording of these process variables. Rugged working conditions such as continuous, extreme, mechanical stress through shock and vibration as well as high temperatures have an influence on the accuracy and reliability of pressure and temperature measuring instruments. Even after just one or two years of service, the reliability of such measuring comes into questions. Have the characteristics of the instrument changed? Are the given readings the same as the measured values? Does the accuracy of the instrument still lie within the specified error limits? Only regular calibration can ensure certainty in this respect.

3.2.1 Introduction to calibration technology

3.2.1.1 Calibration, validation and adjustment

Calibration in measuring technology means determining the deviations in measurement on the finished measuring instrument. No mechanical work is done on the instrument when calibrating. Where indicating measuring instruments are concerned the measured variable is determined by calibrating the deviation in measurement between the display and the correct measured variable or that value which is valid as correct. In the case of material measurement the deviation in measurement between the data on the label and the correct value is determined. For transmitting measuring instruments it is the deviation in measurement between the value of the output signal and the value which this signal must have under ideal transmission conditions and the stated input value.

Adjustment in measuring technology means a measuring instrument (or a material measure) is to be adjusted or compensated so that the deviations in measurement are kept as small as possible or the contributions of the measurement deviations do not exceed the error limits. As a result adjustment calls for an action which generally alters the measuring instrument or the measured material permanently.

The **validation** of a measuring instrument (as well as a material measurement) covers testing and stamping by the responsible calibration authorities in accordance with the calibration standards. It is determined by testing whether the measuring instrument submitted complies with the validation specifications, i.e. whether it meets the demands made on its characteristic data and its measuring technology properties, particularly as to whether the measurement deviation contributions do not exceed the error limit(s). By stamping the instrument it is confirmed that the measuring instrument has met these requirements at the time of testing, and because of its condition it can be expected to remain in the given tolerance range during the period until the stipulated date for revalidation, provided it is handled in accordance with the rules of technology. The law regulates which measuring instruments are subject to mandatory validation and which instruments are not.
The term "validation" is only to be used in its true sense and not for general adjustment and calibration.

3.2.1.2 Calibration traceability

The English word **traceability** describes a procedure by which the measurement indicated by a measuring instrument (or a measured material) can be compared with a national standard. A measuring instrument (or a material measurement) is compared with a standard in each of these steps, the deviation in measurement of which has been determined beforehand by calibration to a higher level standard. This gives a calibration hierarchy as shown in the following Figure 3.18. The Na-

tional Institute of Standards and Technology (NIST) develops and archives the national standards. Certified calibration laboratories have "reference standards" available which are linked directly or indirectly with national standards.

NIST
National Standard

↓

Factory calibration laboratory
Reference standard

↓

Factory calibration laboratory
Working standard

↓

Production
Industrial measuring instruments
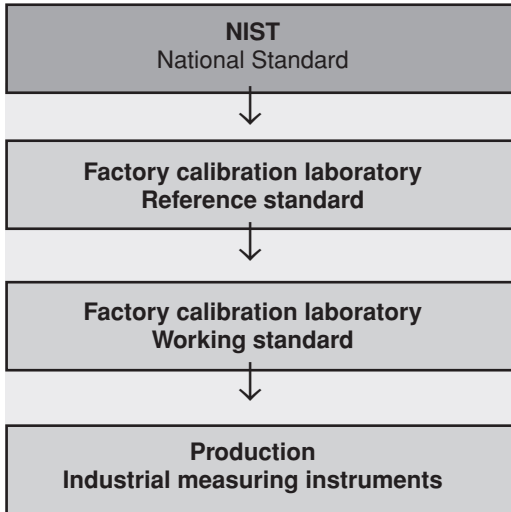
Figure 3.18 Calibration hierachy

3.2.1.3 Uncertainty of measurement when calibrating

The uncertainty of measurements is an estimate of that part of a measurement or calibration result characterizing the range of values within which the true values of the quantity to be measured lies. This is after corrections have been made for all systematic errors. The following observations on uncertainty of measurement are based on the guideline for the expression of uncertainty of measurement in calibrations.

The quantity to be measured (measurand) Y is designated an output or a resultant quantity. It depends upon a number of input quantities X_i (i = 1,2,...v) according to the function G. Therefore, the estimated values y and x_i are used in evaluating the overall uncertainty in the result of a measurement.

$$y = G \, (x_1, x_2, ..., x_i) \qquad (3-9)$$

When considering uncertainty of measurement a difference is made initially between two cases:

a) the measured result is available as a series of measurements which are given from a large number of single values obtained independently from each other under identical conditions.

b) The measured result is the result of a single measurement.

Repeatedly measured quantities

Measurement uncertainty is made up of an incidental component (random error) and a systematic component (random error). **Random error** can be determined statistically by taking repeated measurements under identical, **repeat conditions**. The measured variance is determined by just one observer using one measuring instrument under the same conditions on one measuring object one after the other. As a result systematic errors cannot be recognized. One speaks of comparable conditions when various observers at different places determine a measurand using different measuring instruments of the same type on the same measured object by the same method. The difference in unknown systematic errors can be recognized by making this comparison.

To determine the estimated value x_i for the value X the arithmetical average value $\overline{V}_1$ of the individual, values V_{ij} (j = 1...n), is created from a series of n measurements (n > 10) and corrected by the known systematic error. In this case a residual uncertainty remains through the unknown systematic error neglected during correction, which can only be estimated.

The arithmetic mean-deviation of the single value V_{1j} from the average value $\overline{V}_1$ is called the empirical standard deviation S_{v1}.

$$x_i = \quad _i = \frac{1}{n} \cdot \sum v_{i,j} \qquad (3-10)$$

$$S_{vi} = \sqrt{\frac{1}{n-1} \cdot \sum (v_{i,j} - \overline{v_i})^2} \qquad (3\text{-}11)$$

The estimated value of the variance is given by:

$$S_{xi}^2 = \frac{1}{n} \cdot S_{vi}^2 \qquad (3\text{-}12)$$

Single values and influence quantities

If only one value is known for the value X then it can assumed to be the estimated value X. If certain limiting values upwards $a_{o.i.}$ and downwards $a_{u.i.}$ can be assumed for this value, i.e. error limits of a measuring instrument, this results in the following formulation on the assumption of a rectangular division of the estimated average value and the estimated variance:

$$x_i = \frac{1}{2} \cdot (a_{0,i} + a_{u,i}) \qquad (3\text{-}13)$$

$$S_{xi} = \frac{1}{12} \cdot (a_{0,i} - a_{u,i})^2 \qquad (3\text{-}14)$$

If the difference between the two limit values $a_{o,i}$ - $a_{u,i}$ is designated as $2a_i$ then the equation 3-12 is simplified for the estimated variance:

$$S_{xi}^2 = \frac{1}{3} \cdot a_i^2 \qquad (3\text{-}15)$$

Calculating total uncertainty of measurement

To calculate the total uncertainty of measurement u the single variances S_{xi}^2 of the influencing variable x_i are summarized to give a resulting variance S_y^2. If the measurement variable Y is a linear function of the influencing factor x_1 then the following is valid:

$$S_y^2 = \sum_{i=1}^{v} S_{xi}^2 \qquad (3\text{-}16)$$

In this case v is the number of different influencing variables. The resulting standard deviation S_y is equal to the square root of the variance S_y^2.

In the case of normal distribution the factor K=2 means that the limits of the overall uncertainty are for a confidence level of approximately 95%.
The total uncertainty of measurement u is given through multiplication by a factor k=2 (expanded uncertaintly) in accordance with the equation 3-15:

$$u = k \cdot S_y \qquad (3\text{-}17)$$

In calibration certificates the result of the measurement y and the overall uncertainty u shall be given in the form (y $\pm$ u). An additional note should have the following content:
The reported uncertainty is stated as the standard deviation multiplied by a factor two, i.e. k=2. The standard deviation was calculated from the contributions of uncertainties originating from the measurement standard, from the calibration method and environmental conditions, and from any short term contribution from the object being calibrated.
In calibration certificates the uncertainty of measurement does not take any long term effects into consideration such as the aging of the specimen, for example.

3.2.2 Calibrating pressure measuring instruments

When calibrating pressure measuring instruments the standards and specimens are subject to the same pressure. Calibration is accomplished by comparing the readings provided by the specimen and standard. The standard can also be a reference standard, for example a deadweight tester or a working standard deduced from a reference standard. Differentiation is made between two methods of calibration:

a) calibration according to the specimen reading
b) calibration according to the standard reading.

As a general rule **calibration according to the specimen reading** is used for all dial gauges. In this case the pressure is set so that the pointer with the marking on the dial of the specimen correlates as closely as possible with the required

measuring point. As a result an error through interpolation is excluded when reading the measurand on the specimen. The true value of the measured variance is read off the standard. This is subject to the measuring points being selected so that it is possible for a pointer to cover a mark on the dial.

As a general rule **calibration according to standard reading** is applied for pressure measuring transducers or pressure gauges with digital display. The pressure is set so that the reference reading corresponds with the required pressure value. The value shown is then read off the specimen.

3.2.2.1 Calibrating with deadweight tester

The operation principle of the deadweight tester has been discussed in Section 1.3.1.3. Deadweight testers are used primarily as a reference standard for pressure measurements. WIKA's in-house deadweight testers represent the WIKA reference standards for pressure calibrations from 5"H2O to 150,000 PSI. These deadweight testers are used to calibrate working standards, for example less accurate deadweight testers, quartz Bourdon tube sensors, electrical pressure transducers and precision dial gauges. These instruments represent a broader basis for the working standards, which make efficient calibration possible.

A deadweight tester is often termed a primary standard because the measured variable pressure is deduced from the basic SI units (weight, gravity, area). Deadweight testers are comprised of the basic instrument with one or more piston cylinder systems for different pressure ranges as well as the additional weight sets with 20 to 40 highly accurate **specific weights**. The piston cylinder system may require oil as lubricant to minimize the frictional forces. However, there are also systems which have been designed in such a way that they do not require additional lubricant. Oil or dry air is used as pressure transmission medium.

Figure 3.19   Calibrating a precision dial gauge with deadweight tester.

However, nitrogen, helium, water and diverse hydraulic fluids are also used for specific deadweight testers.

Specific characteristic quantities of a deadweight tester are the precisely measured weights of the masses during their calibration as well as measurement of the effective piston area. This is not measured directly but determined indirectly by taking comparison measurements with other high precision deadweight testers or with **mercury columns**. The sets of weights are made so that the weights in conjunction with the piston cylinder system used provide a nominal pressure value. This nominal value is often sufficient for relatively rough measurements, with accuracies higher than 0.1%. However, if the best possible accuracy of a deadweight tester is needed, then a pressure value calculation has to be made. Factors which should be considered in the calculation of the precise pressure value are; the room temperature which has an influence on the thermal expansion of the piston area, the buoyancy of the weights in the air surrounding them, and the local acceleration due to gravity g_i. These factors are included in the calculation of the force of weight acting on the effective piston area $F=m \cdot g_i$. In this case the

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following formula is used to calculate the pressure:

$$p = g_l \cdot \frac{m \cdot (1 - \rho_L / \rho_M)}{A_0 \cdot (1 + (\alpha + \beta) \cdot t\text{-}20) + \lambda p_e)} \cdot 10^{-5}$$

with p in bar   (3-18)

In this case g_l is the local acceleration due to gravity, $\alpha + \beta$ the temperature coefficient for the piston cylinder system, λp_e the coefficient of deformation of the pressure loaded piston, m the total of all given weights, A_0 the piston area at 20°C, ρ_L the density of the air during measuring and ρ_m, the density of the masses.

Calibrating pressure gauges with low measurement uncertainty

Precision pressure gauges (uncertainty of measurement $\leq 0.1\%$) are calibrated as a general rule directly on the reference standards. The specimen must be set up in an air-conditioned measuring room for at least 12 hours to adjust to the required temperature. The measurement arrangement is set up so that the reference norm and specimen are on one level (the reference level) to eliminate pressure differences through differences in altitude. Each measuring point is first run with rising pressure, and once the pressure has stabilized the specimen and standard are compared with each other. After the testing point maximum value has been attained with the highest pressure, a waiting period of at least 10 minutes has to be observed before the measuring points are set in the direction of falling pressure one after the other in a second series of measurements. In the rising pressure direction the measured value must always be to the standard value. Similarly, in the falling pressure direction the measured value must be the standard value.

3.2.2.2 Calibrating with the quartz Bourdon tube controller

The quartz Bourdon tube manometer as working standard

The standards derived from the reference standard (so-called **working standards**) can be, for example, low precision deadweight testers, quartz manometers, electrical pressure transducers using different sensor principles (vibration cylinder, quartz tuning fork, piezoresistive, DMS) and even precision pressure gauges which have been previously calibrated on the reference standard.
Quartz Bourdon tube manometers and electrical pressure transducers with vibrating cylinders and quartz tuning forks have already been described in Section 1.3.2.2. These instruments are suitable as working standards because of their high stability and good measured value reproducibility, for daily calibration of industrial pressure sensors, for example. The quartz Bourdon tube manometer, which together with a precision pressure control facility forms a **quartz Bourdon tube controller**, is especially suitable.
The pressure measuring ranges of these quartz Bourdon tube controllers are between 70 mbar and 170 bar. As a general rule nitrogen or dry air are used as the testing medium. Moreover, quartz Bourdon tube controllers can also be designed for absolute pressure (15 PSI and up) and differential pressure calibrations, and they can be equipped with a computer interface. This allows a calibration facility with which a stable pressure can be precisely set and measured very accurately. Calibrating with the quartz Bourdon tube controller can therefore be easily automated, particularly when the specimens are pressure sensors with an electrical output signal.
The uncertainty of measurement of these instruments is approx. 0.01% of full scale. The quartz Bourdon tube manometer is located within the temperature-controlled sensor chamber of the controller; as a result it is very stable over a long period of time and only needs to be recalibrated once a year.

Calibrating pressure transmitters

Pressure transmitters are supplied from a stabilized voltage source for calibration. The voltage is set so that it complies with the mean value of the limit values for the auxiliary current shown on the rating plate, which is 20 V as a general rule. The voltage output is connected up to a suitable digital multimeter. Where transmitters with current output are concerned an external shunt with a resistance of 100 ohm is generally used. After preheating for a period of approx. 30 minutes, the testing pressures are set one after the other by the computer-control system in a rising and falling procedure with the quartz Bourdon tube controller and the measured values registered by the digital multimeter. The results are fully analyzed by PC. This also includes generating the calibration certificate which is printed out immediately after the measurements have been taken.

Figure 3.20   Automatic calibration work bench for pressure sensors

3.2.2.3 Calibrating with mobile calibration units

Portable pressure calibrators are used mainly in the service sector. In these cases, the measuring instrument often cannot be removed from the plant, or only with very great difficulty, and calibrations are made on site. This has the advantage that the deviation in measurement of the entire measurement chain comprising pressure transducer, cable and indicator or evaluation unit, respectively, can be determined.

In this case the measuring instruments for testing, especially manometers, are connected up with a pressure hose to the testing pump of the calibration system and subjected to the testing pressure. A portable calibration system, for example the **PCS system from WIKA**, is made up of a pneumatic or hydraulic hand pump with which testing pressures can be generated from as little as a few inches of H_2O to 15,000PSI. Electrical pressure transducers are used here as the standard. These have been previously calibrated together with a digital hand measuring unit, for example the WIKA **handheld service manometer**, to a higher ranking standard. For calibrating purposes, the standard and specimen are threaded into an appropriate adapter and put under pressure by the testing pump. Precision adjustment is made using an adjustment screw on the pump with which the pressure on the manometer under test can be set accurately by varying the volume of the testing pressure. The actual pressure is read off the digital display with an uncertainty of 0.25% based on the upper limit of the effective range of the standard.
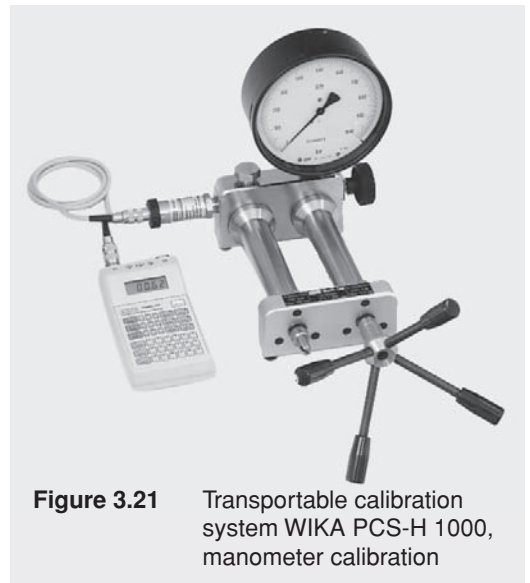
Figure 3.21   Transportable calibration system WIKA PCS-H 1000, manometer calibration

3.2.2.4 Error explanations for calibrating pressure gauges

According to the procedure described in Section 3.2.1.3, the uncertainty of measurement is determined for two typical calibration operations from the influencing factors that occur with the respective calibration.

Calibrating a quartz Bourdon tube manometer with a deadweight tester

As an example, calibration at a pressure of 100 PSI (air) with a calibrated deadweight tester as the standard is described. According to the calibration certificate the uncertainty of measure u of the standard is $\pm$ 0.01% of the measured value. The pressure measured with the deadweight tester is adjusted to remove the known systematic error. The quartz Bourdon tube manometer is equipped with a 400 PSI sensor. As can be seen from the data sheet, the maximum measurement error is 0.005% of the upper limit of the effective range due to reproducibility and stability in the temperature range of 50°F to 86°F. This value is assumed for the short term specimen. The digital display used for showing the measured signal causes an additional uncertainty of 0.01% based on the respective value of the output signal; therefore, a measurement error of $\pm$ 0.01 PSI must be considered at 100 PSI. The maximum hysteresis that occurs during measurement is estimated at 7.5 · 10^{-3} PSI. Leveling out during calibration compensates for the error due to the difference in altitude between standard and specimen.

Calibrating dial gauges with the deadweight tester

As an example the calibration at a pressure of 1000 PSI (air) with a calibrated deadweight tester as the standard is described. According to the calibration certificate the uncertainty of measure u of the standard is $\pm$ 0.01% of the respective measured value. The dial gauge, Type 342.11, which is to be calibrated has an accuracy of $\pm$0.1% of span. The reading error is assumed to be $\pm$ 0.2 PSI and equal to 1/5 of the scale division. Fluctuations in ambient temperature of $\pm$ 1 K causes errors in the measured results by the dial gauges with 0.004%/K up to $\pm$ 0.4 PSI. The maximum hysteresis that occurs during measurement is estimated at 0.2 PSI. Leveling out during calibration compensates for the error due to the difference in altitude between standard and specimen.

Error source	i	a_i in psi	a_i^2 in psi²	S_{xi}^2 in psi²	Note
Standard	1	$1.45 \cdot 10^{-2}$	$2.10 \cdot 10^{-4}$	$0.701 \cdot 10^{-6}$	acc. to eq. 3-15
Short-term specimen stability	2	$1.81 \cdot 10^{-2}$	$3.29 \cdot 10^{-4}$	$1.10 \cdot 10^{-4}$	acc. to eq. 3-15
Temperature influence of specimen	3	$1.45 \cdot 10^{-2}$	$2.10 \cdot 10^{-4}$	$0.701 \cdot 10^{-6}$	acc. to eq. 3-15
Uncertainty through hysteresis	4	$1.09 \cdot 10^{-2}$	$1.18 \cdot 10^{-4}$	$0.394 \cdot 10^{-6}$	acc. to eq. 3-15
Resulting variants Sy^2 in psi²				$2.89 \cdot 10^{-4}$	acc. to eq. 3-16
Resulting standard deviation, Sy in psi				$1.70 \cdot 10^{-4}$	
Total uncertainty of measurement, $\pm$ u in psi (k = 2)				$3.40 \cdot 10^{-4}$	acc. to eq. 3-17

Table 3.9 Uncertainty of measurement when calibrating a quartz bourdon tube manometer with a deadweight tester

Error source	i	a_i in psi	a_i^2 in psi^2	S_{xi}^2 in psi^2	Note
Standard	1	0.145	$2.1 \cdot 10^{-2}$	$7.01 \cdot 10^{-3}$	acc. to eq. 3-15
Temperature influence of specimen	2	0.58	$3.36 \cdot 10^{-1}$	$1.12 \cdot 10^{-1}$	acc. to eq. 3-15
Reading error of the specimen	3	0.29	$8.41 \cdot 10^{-2}$	$2.8 \cdot 10^{-2}$	acc. to eq. 3-15
Uncertainty through hysteresis	4	0.29	$8.41 \cdot 10^{-2}$	$2.8 \cdot 10^{-2}$	acc. to eq. 3-15
Resulting variants, Sy^2 in psi^2				$1.75 \cdot 10^{-1}$	acc. to eq. 3-16
Resulting standard deviation, Sy in psi				$4.18 \cdot 10^{-1}$	
Total uncertainty of measurement, $\pm$ u in psi (k = 2)				$8.37 \cdot 10^{-1}$	acc. to eq. 3-17

Table 3.10 Uncertainty of measurement when calibrating a dial gauges with a deadweight tester.

3.2.3 Calibrating temperature measurement instruments

The term "calibrating a thermometer" is understood to mean determining the deviation in measurement of a thermometer.

The deviation in measurement is the difference between the true temperature of the thermometer and the indicated temperature or the output signal, respectively. Here one differentiates between two different calibration methods as a general rule.

a) When **calibrating at fixed points** the specimen is subjected to a known temperature which is equivalent to the reproducible, well-defined state of equilibrium, for example, the temperature of solidified zinc in a zinc point cell.

b) When **calibrating by comparison measurement** a standard thermometer and the specimen are subject to a constant temperature which, for example, is generated by a stirred liquid bath. The bath temperature is measured with the standard and compared with temperature displayed by the specimen.

Fixed point calibrations are performed on materials suitable for solidification, melting and triple-points. The conversion temperatures of these materials, in this case purest metals, gases and water, are defined in the ITS-90 standards. Calibration by comparison measurement is more preferred compared to the necessary expense to prepare the majority of fixed points. The standard thermometer and specimen are brought up to the same temperature by putting them together in a tempering unit. Once thermal equilibrium has been established between thermometer and calibration bath, the display (output signal) of the specimen is compared with the standard thermometer. Precision Pt resistance thermometers, also known as standard resistance thermometers, are used as reference standards. Should other precision thermometers be calibrated by comparison with standard resistance thermometers, these can also be used as standards for calibration purposes. Above 900°F it is common to use platinum thermocouples as standards.

Temperature block calibrators are often used today to simplify calibration of industrial thermometers on-site. These have a thermally insulated, temperature controlled metal block with holes. A permanently installed Pt resistance thermometer serves as the standard and control thermometer. Calibration is done by comparing the temperature displayed by the calibrator with that shown by the specimen or its output signal, respectively.

3.2.3.1 Calibration by fixed points

Standard resistance thermometers conforming with ITS-90

ITS-90, the 1990 international temperature scale, defines special types of Pt resistance thermometers for use as standards from-430°F to 1760°F (-259°C to 962°C). Design requirements and details are described in greater depth in "Supplementary information for the international temperature scale of 1990". Standard resistance thermometers calibrated to fixed points conforming with ITS-90 are used for calibration by comparison measurement to determine the true temperature in the calibration baths. Formulas and tables are given in their calibration certificates with which the measured resistance value can be converted into temperature. The resistance of the standard thermometer is measured with A.C. resistance measuring bridges. Three versions of standard resistance thermometers are typical.

Capsule thermometers

Capsule thermometers for low temperatures (Figure 3.22), with a range of application from -420°F to 400°F (-250°C to 200°C), are suitable for installation in cryostates due to their small design. These are used as calibration baths for comparison measurements at low temperatures. In this case the platinum coil is insulated in a thin quartz glass tube (B), in about a one inch (50 mm) long platinum housing tube (A) with a diameter of 5 mm. Two double connection wires are welded to the ends of the coil (C). The wires are fused in a glass sheath (D) which seals the housing tube hermetically. The resistance of the measuring coil is approx. 25 Ω at the water triple-point (0.018° F).
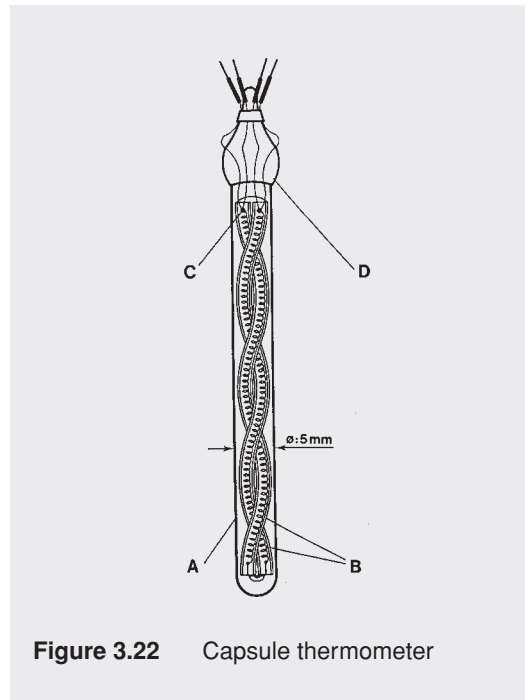
Figure 3.22   Capsule thermometer

Standard resistance thermometers

As a rule, standard resistance thermometers for the range −310°F to 1100°F (-189°C to 600°C) (Figure 3.23) are 500 to 600 mm long and have quartz glass housing tubes measuring 7 to 8 mm in diameter, or less often metallic tube casings, in which the temperature sensor and connection wires are housed. In such cases the platinum measuring coil made of wire, 0.05 to 0.1 mm in diameter, takes the form of a double helix on a carrier of quartz glass, sapphire or ceramic, which has a cross section in the form of a cross and forms the temperature sensor. Since the majority of calibrations take place in the above-mentioned temperature range this form of standard thermometer is frequently found in calibration laboratories. The resistance of the measuring coil is also approx. 25 Ω at the water triple-point.

Figure 3.23 Typical measuring coil of a standard resistance thermometer for temperatures up to 1200°F

Standard resistance thermometers for high temperatures

Standard resistance thermometers for a temperature range from 32°F to 1750°F (0°C to 962°C) are at least 600 mm long and only have a quartz glass housing tube. The platinum wire is wound on a quartz plate, and because of its mechanical tensile strength, which deteriorates at high temperatures, it is approx. 0.4 mm in diameter (Figure 3.24). As a result, a lower resistance is given at the water triple-point, which is between 0.25 and 5 Ohm. Particular attention must be paid to quartz glass **devitrification**, which can be caused by slight contamination of the surface (for example, through marks left by fingerprints) at high temperatures. In this case the quartz glass can crystallize or shatter. Devitrification can be avoided by cleaning the quartz tube with ethanol or 65% nitric acid.

Contamination of the platinum by metal vapors, for example Cu, Ni, Fe and Cr, which diffuse through the glass tube at high temperatures, leads to increased aging of high temperature standard resistance thermometers.
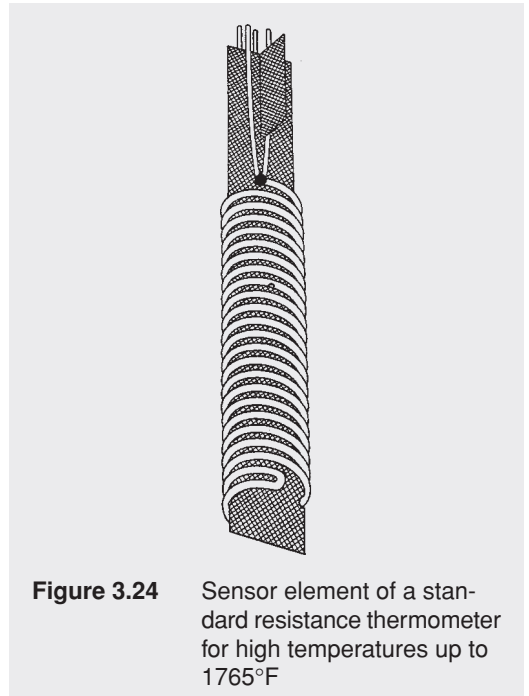
Figure 3.24 Sensor element of a standard resistance thermometer for high temperatures up to 1765°F

A standard resistance thermometer is generally connected to the measuring instrument in a 4-wire circuit. For all types the basic material must be extremely pure and processed very carefully, because the slightest impurity will lead to fast aging and changes in the temperature coefficient. The measuring coil is made of spectrally pure platinum. It should be mounted free of mechanical stress on the carrier body. The pre-assembled housing tubes of the standard resistance thermometers are evacuated and filled with a noble gas before sealing. A small amount of oxygen is added to the noble gas to prevent a reducing atmosphere in the thermometer.

Compared with **physically pure platinum**, from which Pt 100 measuring resistors are made, spectrally pure platinum has a higher temperature coefficient of $3.925 \cdot 10^{-3} \text{ K}^{-1}$. In ITS 90 this property is expressed by the resistance ratio required for standard resistance thermometers by the melting

point of galium and the water triple-point $W_{(GA)}$, which must be greater or equal to 1.11807; $W_{(GA)}$ = R (29.7646°C) / R (0.01°C). Standard resistance thermometers are outstanding for the very high reproducibility of their resistance values and minimal aging, which is typically 1 mK to 2 mK (per 1000 working hours) in the case of thermometers for maximum application temperatures up to 1200°F.

Fixed point calibration

Fixed points are used for exact calibration of Pt standard resistance thermometers to ITS-90. These fixed points are **equal phase weights** made of purest materials (solidification, melting and triple-point). These materials, their fixed point temperature and the form that the cells take in the material are likewise specified in ITS-90. A protective tube with an inner diameter of approx. 8 mm is installed in the fixed point cell to hold the specimen. It is heated up in a liquid bath or in a one or multi-zone furnace. During the phase transitions a constant temperature is generated within the cell with very high reproducibility. Fixed point cells can hold open or closed glass vessels which contain the appropriate material in purest form ($\geq$ 99.9999%). Where metal solidification points are concerned the fixed point metal should be contained in a graphite cup within a quartz glass container. Fixed point calibration follows with very low uncertainties of measurement, 0.5 mK to 5 mK being typical in the range of 32.018°F to 1200°F. Since fixed point calibrations involve high equipment costs and time, except for calibration with the water triple-point, the application of fixed calibration is generally only used by large institutions. For this reason this process is detailed here at any great length, with one exception.
In industrial calibration laboratories the triple-point of water is used for regular control of standard thermometers because any change to the thermometer will also be observed as a change in resistance at the **water triple-point**. The triple-point cell, for example, is pre-cooled to approx. – 20°F and frozen throughout by carefully shaking

in an axial direction. A uniform, complete mantle of ice must form around the inner tube of the cell. To keep the heat exchange of the cell with its surroundings low, the cell is subsequently tempered in a bath at approx. 32°F. Located on the inside of the cell are the three phases of purest water in a state of equilibrium. This is equivalent to a fixed temperature of 32.018°F, which can be shown with high temporal consistance and very good reproducibility. Independent of the external heat exchange of the cell the latent heat from the phase conversion inside the cell leads to homogeneous temperature distribution near the phase limit. An uncertainty in measurement of 5 mK is possible with the water triple-point.

Triple-point cells are made of a cylindrical borosilicate glass body in which an inner tube is fused. The space between the tube is filled to approx. 80% with purest (distilled) water and sealed under the vapor pressure of boiling water.
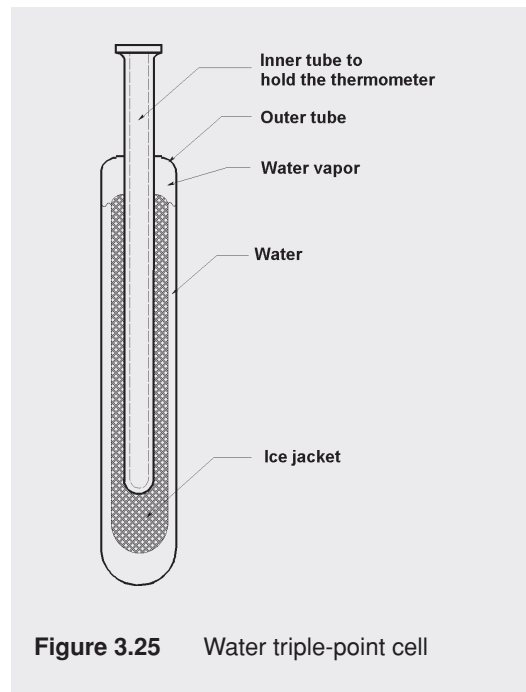
Figure 3.25   Water triple-point cell

Calibration

The frozen triple-point cell can, for example, be heated in an agitated liquid bath with a mixture of glycol and water. For this purpose it is set up vertically in the bath so that the outer glass body is completely immersed with only the inner tube protruding. Approx. 2 - 5 ml alcohol is placed in the inner tube to improve the heat contact. The pre-cooled specimen is put into the cell. It has good thermal contact with the slowly melting ice mantle, with the alcohol acting as transmission media. After approx. 15 to 20 minutes, thermal equilibrium will be achieved and the measured values can be recorded. It is recommended that at least three measurements be taken at intervals of 5 minutes or, should an electrical thermometer with a computer interface be used, the measured values should be continuously recorded. Fluctuations $\pm$ 1 mK occur with precision Pt resistance thermometers in conjunction with alternating current resistance measuring bridges. Cells in the liquid bath remain ready for use for approx. 8 hours depending upon the number of installed thermometers. If many specimens are to be calibrated, the cell should be taken out of the bath and checked between times. The cell can be used as long as a closed mantle of ice is around the inner tube. If the temperature in the bath is too low then the cell will be completely frozen and generally destroyed as a result. Should the cell thaw too quickly, then only a few thermometers can be calibrated. Optimal controller adjustment must be determined by experiment.

Notes on using the triple-point cell

The triple-point cell in a bath is a really practical method. The cell can be frozen easily and quickly and kept ready for use. Should an even lower uncertainty of measurements be required ($\leq$ 5 mK), then the "classical" triple-point method should be used. In this case the inner tube of the cell is cooled with dry ice, rotated around its longitudinal axis and the ice mantle frozen on the inner tube in a defined manner. This method takes considerable time and is only mentioned here to be complete. Working instructions for this method can be obtained from the cell manufacturers.

Resistance measuring bridges

Apart from the properties of the thermometer and the uncertainty of the fixed point, it is the precision of the resistance measurement which decides the uncertainty of measurement when calibrating thermometers. Exact resistance measurements in 4-wire circuits can be obtained with **alternate current resistance measuring bridges**. Parasitic thermal voltages, which falsify the measured result where direct current measurements are concerned, will be eliminated. The outstanding advantage is the use of inductive voltage dividers. Such dividers with relative errors of 10^{-6} to 10^{-8}, very good long-term stability and low output resistances allow bridge constructions with resolutions up to 10^{-5}K. The relationship between the resistance of the thermometer and a standard resistance is measured with alternate current resistance measuring bridges. Usable standard resistances have temperature coefficients $\leq 3 \cdot 10^{-6}$ K^{-1} ($23°C$), an AC/DC error $\leq 10^{-6}$, and aging $\leq 2 \cdot 10^{-6}$/a and can be calibrated with relative uncertainties of measurement $\leq 10^{-6}$.

Standard resistances are tempered in a thermostat to $\pm$ 0.1 K to 0.01 K so that their temperature coefficient is not affected. A constant, adjustable low frequency measuring current, which flows through the coil of the thermometer and standard resistance, is generated for measurement. The drops in voltage through the two resistances are compared with each other; the larger of the two voltages is split so that it corresponds with the voltage drop through the smaller resistance. A zero indicator with a differential amplifier shows the voltage equivalence. The set divider ratio corresponds to the ratio of the two resistances (Figure 3.26). To eliminate the influence of the cable capacities and residual inductivities, an appropriate circuit ensures the same phase angle of the voltages at the input on the differential amplifier.

Uncertainties of measurement which are less than 1 mK when converted can be obtained over a wide temperature range with this measuring method with the usual 25 ohm and 100 ohm resistance thermometer available through the trade.
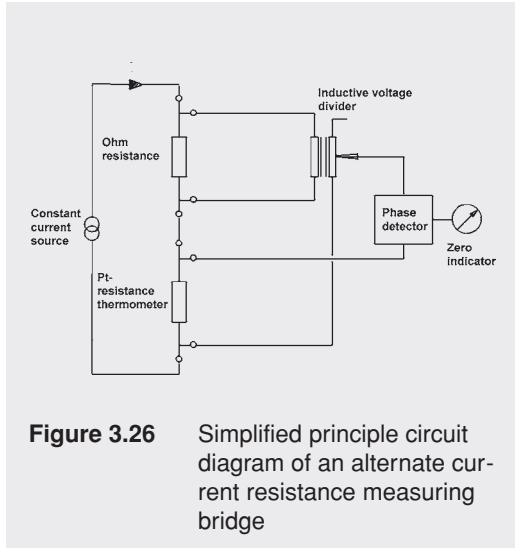
Figure 3.26   Simplified principle circuit diagram of an alternate current resistance measuring bridge

3.2.3.2 Calibrating by comparison measurement

Calibrating in thermostatic baths

Standard thermometers and specimens for calibration are brought up to the same temperature in a calibration bath with the help of a contact material so far as possible. As soon as the thermometers and the contact material are in a state of thermal equilibrium, the temperatures of the specimens are to be read or the measured values recorded, respectively, and compared with the temperature measured with the standard thermometer. A calibration bath is also required in addition to the standard thermometer and an appropriate resistance measuring instrument to achieve a low uncertainty of measurement or low transmission error, respectively. This bath has to ensure homogeneous spatial temperature distribu-

tion as well as high temporal temperature constancy in the measuring chamber.

Agitated liquid baths

Homogeneous spatial temperature distribution and a highly constant temporal temperature can be best achieved in agitated liquid baths. The geometry of the bath, the tempering liquid used and also the temperature at which it is calibrated, affect these properties to a high degree. This is why the temperature distribution and temperature fluctuations are to be determined by experiment at different temperatures and with different media before a new calibration bath is put into use.

As a general rule a liquid bath should have an adequate installation depth for the thermometer, be sufficiently large in volume with due consideration to the constant temperature, and have a fast regulation system. Installation depths of 12 inches and a volume of approx. 6 gallons are adequate as a general rule. Stirrers or pumps must run without vibration and must not transfer any additional heat to the bath. The heater is equipped with two independent heating circuits with different capacities, making it possible to precisely regulate the heating, for example, so that when the desired temperature has been reached a larger adjustment range is available by switching over to lower capacity. To reduce temperature gradients heating and cooling elements should not be physically separated in calibration baths with integrated cooling, but be thermally coupled. Good ambient thermal insulation of the bath is required.

Bath liquids

Specific properties such as good heat conductivity, high thermal capacity and low viscosity are preferable as well as adequate circulation of the liquid. The bath fluids should be inert as much as possible, have a low vapor pressure and not decompose chemically. They should not be flammable but should retain their properties as far as

Range	Medium	Properties
-110°F to 32°F	Methanol	Becomes viscous through absorption of water, toxic, flammable
-40°F to 140°F	Water/glycol	Becomes viscous through absorption of water, to a certain extent toxic
50°F to 195°F	Water	Conductive, very good thermal properties
120°F to 400°F	Silicone oil	Relatively high vapor pressure, difficult to remove
400°F to 950°F	Sodium nitrate	Chemically aggressive, must not come into contact with flammable materials

Table 3.11 Commonly used bath liquids

possible over a wide temperature range. In practice there is no single liquid meeting all these requirements. This is why different liquids are used in the different ranges (see Table 3.11).

In this respect a selection is made in practice on an individual basis and generally a liquid with better thermal properties is preferred independent of its hazard risk. Thermometers can be immersed directly in the liquid except in the case of sodium nitrate. When using sodium nitrate, which does not become liquid until over 320°F, the installation of thermometers in thin-walled protection tubes made of heat- and corrosion-resistant steel is recommended.

Calibrating a bath

Temporal temperature fluctuations and spatial differences in temperature in the measuring area (or better in the **calibrating section**) within a bath are to be determined when calibrating in order to make allowance for them when calculating the uncertainty of measurement. Calibration can be carried out with non-calibrated thermometers since the measurements concern differences in temperature.
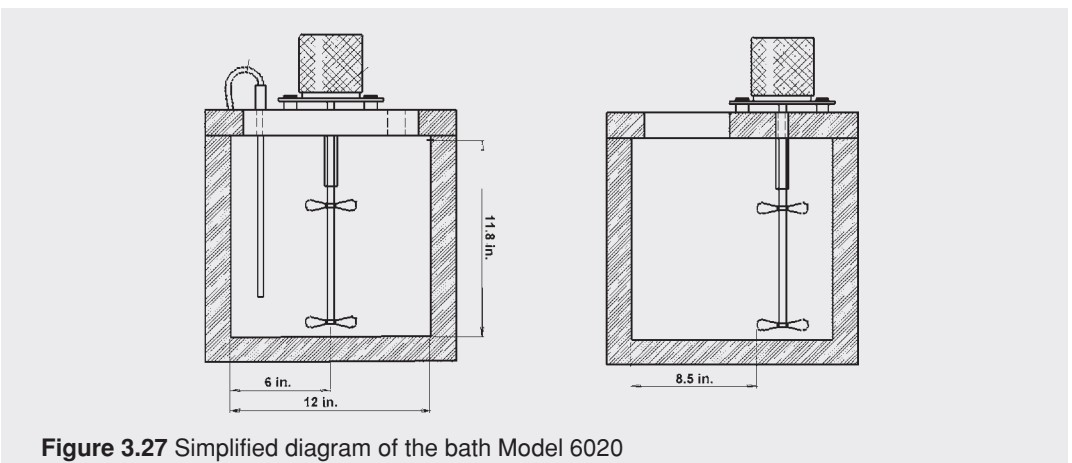
Figure 3.27 Simplified diagram of the bath Model 6020

Calibration can be performed with non-calibrated thermometers since only the difference in temperatures measurements is a concern.

The liquid baths in the WIKA calibration laboratory are evaluated by resistance thermometers with a 4 mm diameter and 400 mm length using the following methods. Only bath Model 6020 using a silicone oil M 50 liquid is described here. The calibrating range within the bath must be determined before calibrating. The thermometers can be positioned a small distance apart using a fixture. Figure 3.27 shows a cross-section of the liquid bath.

Definition of calibrating area

The specimens and the standard thermometers are arranged upright while evaluating. The ends of their stems with the measuring element should be located in the bottom third of the bath at an immersion depth of approx. 11 in., almost touching each other. This arrangement has proven to work well when calibrating up to 8 thermometers at a time. Under these conditions the calibrating

Figure 3.28 Definition of calibrating area

area is in the form of a cylinder with a maximum diameter of approx. 4 inches. This range begins in the middle of the bath opening and ends ∫ inches from the bottom. The liquid level of the bath is 11.8 inches. The spatial temperature distribution has been determined at 3 levels at an immersion depth of 7.25, 9.25 and 11.25 inches. Because the inherent heat conductivity of the thermometers leads to errors in the measured results, no measurements were taken above an immersion depth of 7.25 inches.

Measuring temperature distribution

The differences in temperature were measured in vertical and horizontal directions in the calibrating range (Figure 3.29). The resistance measurements of the three thermometers were taken with a 6 1/2-digit digital multimeter linked to a computer for direct evaluation and conversion of the temperature resistance.

All the temperatures given are average values from 20 measurements taken over a period of 7 minutes. The thermometer T_1 was always in the center of the measuring tank. The thermometers T_2 and T_3 are arranged to the left and right next to T_1 with their tips touching. When determining the radial temperature distribution the deviation of the thermometers to each other (i.e. the offset) has to be first determined at the respective testing temperature: $\delta_{21} = T_2 - T_1$ and $\delta_{21} = T_3$. After this the thermometers T_2 and T_3 are put into positions T_2 and T_3 and T_2'' and T_3''. The measured differences in temperature to the thermometer T_1 are then calculated as $\delta_{21}' = T_{2'-T1}$ and $\delta_{21}'' = T_2'' - T_1''$. The same applies accordingly for thermometer T_3. The measurements in WE and in NS direction were taken for all testing temperatures at three determined measuring levels.

To measure the actual temperature distribution the three thermometers were first immersed to a depth of 9.25 inches in the center of the calibrating range. After the deviation to each other had been measured the T_3 was immersed to 11.25
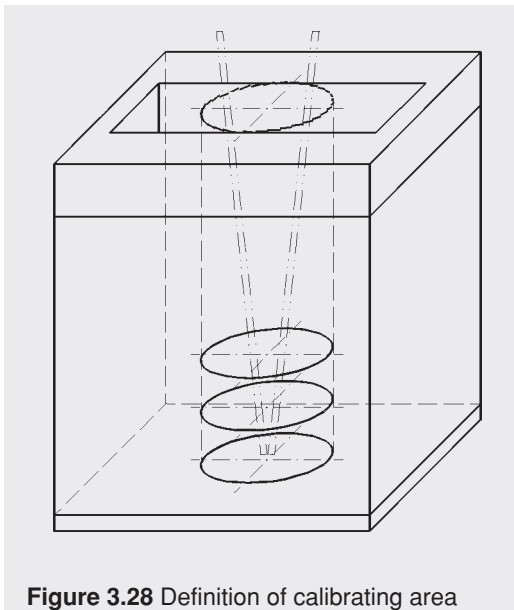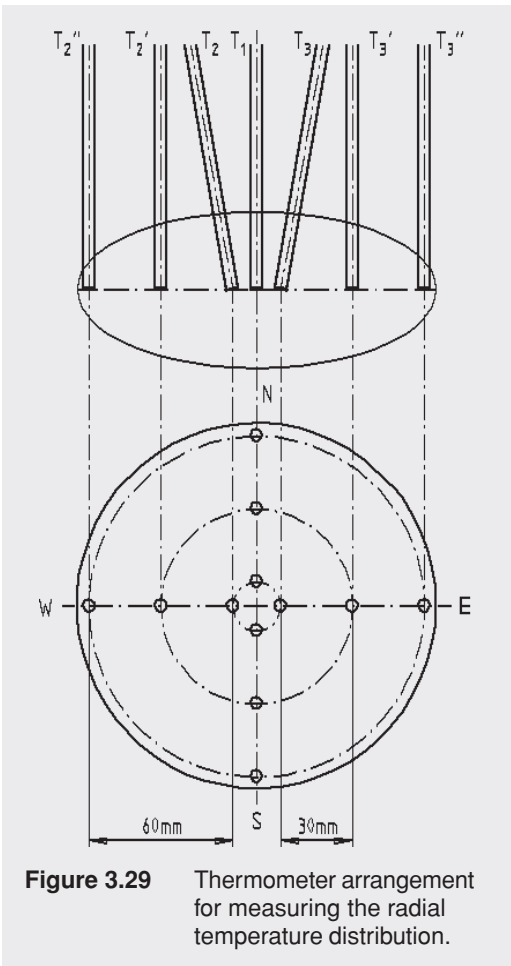
Figure 3.29 Thermometer arrangement for measuring the radial temperature distribution.

inches and T_2 to 7.25 inches but T_1 remained in its position.

The differences to the first measurement are equivalent to the vertical temperature gradients (see Table 3.12). The error contribution of the inhomogeneous temperature distribution was determined as $\pm$ 4 mK in the inner graduated circle (1.2" radius) and $\pm$ 7 mK in the external graduated circle (2.35" radius).

Recording temperature stability over time

A thermometer was immersed in the center of the calibration range to a depth of 9.25 inches for recording the temperature stability over time. After the desired temperature was reached, the systems were switched over to the small heating element (200 W) and the temperature was recorded over a period of 90 minutes. The bath temperature during this period was on average 99.981°C (211.965°F) $\pm$ 1.8 mK.
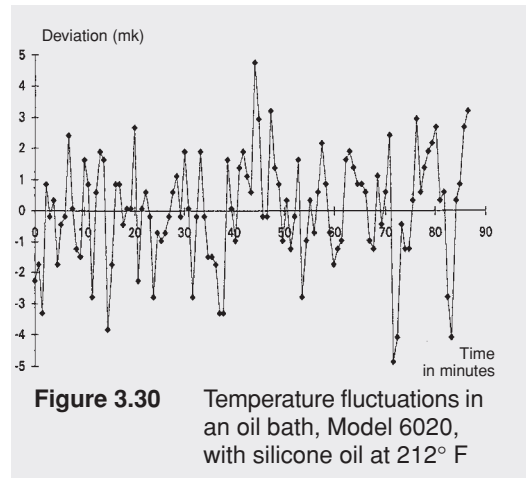
Figure 3.30 Temperature fluctuations in an oil bath, Model 6020, with silicone oil at 212° F

immersion depth	vertical central	WE - measurement, horizontal				NS - measurement, horizontal			
		δ_{21} " 2.36"	δ_{21} ' 1.18"	δ_{31} ' 1.18"	δ_{31} " 2.36"	δ_{21} " 2.36"	δ_{21} ' 1.18"	δ_{31} ' 1.18"	δ_{31} " 2.36"
7.25 in.	- 1.8	9	7.2	- 5.4	- 7.2	- 10.8	- 7.2	1.8	0
9.25 in.	0	- 9	3.6	- 3.6	- 3.6	- 10.8	- 7.2	7.2	12.6
11.25 in.	1.8	- 11	- 1.8	- 3.6	0	- 10.8	- 7.2	5.4	12.6

Table 3.12 Temperature distribution measurement at 212° F

How calibration is performed using resistance thermometers as an example

Resistance thermometers are annealed for several hours at approx. 50°F above their maximum testing temperature after initial measurement at the water triple-point (ice point). After this they slowly cool down to room temperature in still air and are again measured at the triple-point. After two to three aging cycles the change in the triple-point resistance must drop towards zero. Standard resistance thermometers also show changes of $\leq$ 1 mK after a longer dwell time at 930°F, for example. Industrial platinum resistance thermometers show considerably greater changes. This specimen instability and other causes, which could lead to a non-repeatable curve, must be carefully analyzed because they are generally the main contributing factor in the total uncertainty of measurements. Measurement recording starts once thermal equilibrium is reached between the thermometers in the bath. The measured values are recorded with the help of a computer over a period of time, which must be longer than the response time T of the "slowest thermometer". The measured values can be recorded over several hours for exact measurements. Standard thermometers and specimens are connected up to a resistance measuring bridge at regular intervals by a changeover switch and the measured values are recorded. The period of time with the lowest fluctuations in temperature can be selected from the recorded data. It is best to set a stability criterion S_{max} and a number of n measurements for every day measurement to shorten calibrating times. The last n measured values are entered into a memory on a **first-in-first-out basis**. The mean value is determined from these n measured values and then the standard deviation is calculated. The measurements are taken until the standard deviation of all thermometers has become less than the stability criterion S_{max}. Short-circuiting and a standard resistance can be used advantageously in the measuring cycle for **quick calibration** of electrical resistance measuring devices.

Calibrating in dry block calibrators

A dry block calibrator is typically used at a temperatures between 900°F and 2100°F (Figure 3.31). A simple dry block calibrator is made of a ceramic heating tube (1) with a typical inner diameter of 3 in. and 26 in. length. The heating coil (3) which is vacuum-wrapped by ceramic fibers designed for a maximum operating temperature of 2400°F. To overcome the drop in temperature at the ends of the oven, the heating coil is sealed off at the ends of the tube. The insert (2) is made of nickel or heat-resistant steel, and has 6 to 8 holes in a concentric arrangement (6" deep) to hold the specimens (5) and the standard (6). Due to its construction and its thermal mass, the insert improves temperature distribution in the oven's calibrating range. The heating tube is very well insulated from the external environment (4).
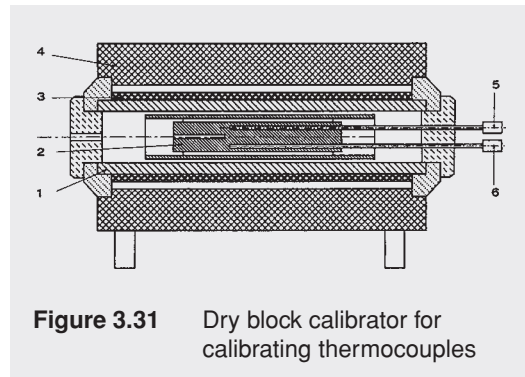
Figure 3.31   Dry block calibrator for calibrating thermocouples

Evaluating the dry block calibrator

Like liquid baths, the temperature distribution and stability of tube must be determined. The cylindrical insert in the middle of heating tube improves the temperature profile in the vertical direction and reduces temperature fluctuations, which are greater than in liquid baths. The insert has 6 to 8 holes approximately six inches deep to hold the specimens. These holes are arranged concentrically because it can be assumed that the same temperature exists at the same radii in the cylinders. To evaulate, first the temperature as a func-

tion of immersion depth is determined in 100°F steps for the entire working range. Up to 900°F it is possible to insert two resistance thermometers of the same type in the blind holes as well as thermocouples in the other holes towards the ends. While one thermometer remains in position the second thermometer in the series is drawn out and the difference in temperature recorded, for example, in one-half inch steps. Differences in temperature between the holes are determined using two or more thermometers which are replaced with each other in the given cycle after each measurement has been taken. Fluctuations in time are recorded. In this case there should be no differences between holes of the same diameter. When taking any measurements in the oven, care must be taken to ensure that the heating tube is sealed at both ends. Mineral wool is best used at the end where the thermometers stick out.

Preparation for calibrating

The cold oven is provided with the proper insert for the testing temperature range and the specimens. Inserts made of pure nickel have proven successful for temperatures from 900°F to 1800°F and Sicromal and ceramic up to 2200°F. The insert is positioned in the middle of the heating tube and should be grounded (if the heating voltage is > 60 V) because the conductivity of ceramic increases at high temperatures. As a general rule the diameter of the hole should be as small as possible allowing for the thermal expansion of specimens. Too large an air gap between the thermometer and the hole has a detrimental effect on heat transmission and can lead to considerable measuring errors. At temperatures above 900°F experience has shown for sheathed thermocouples with a 6 mm diameter, air gaps of 0.2 to 0.5 mm falsify the measured result by approx. 0.1 K to 0.5K. In addition to the air gap, the error depends on the temperature and thermal conductivity of the insert and thermometer, so generally no factual figures can be given.

How to calibrate by taking thermocouples as an example

All thermocouples having an adequate installation depth for the dry block calibrator (as a rule 16 inches) and not exceeding 0.3 inches in diameter because of the low heat dissipation error are suitable for calibrating. Bare thermo-wires have to be previously inserted into protective ceramic-capillary tubes. New thermocouples must be annealed over 30 to 40 hours at approx. 50°F above their maximum service temperature before calibrating in order to relieve non-homogenous properties. With used thermocouples, annealing for over 3 to 4 hours will generally be sufficient. The cold junction temperature is considered for thermocouples; this is not the case with other thermometers. The thermo-wire or compensation cable and copper measuring cable are soldered to each other and insulated from each other. The cross section of the copper measuring cable should not exceed 0.5 mm². The ends of the cable with the soldering points are threaded into a thin-walled glass tube approx. 10 inches in length and subject to the cold junction temperature. Mineral insulated thermocouples can be extended to the cold junction, if necessary, with a calibrated compensation cable. Electronic cold junction compensators with typical uncertainties of 0.5 K and over cannot be used for calibration purposes. The following compensation methods are recommended for calibrating.

Cold junction compensation in ice point

The glass tube with the cold junction is inserted in a dewar vessel approx. 7.5 inches in height filled with a mixture of crushed ice and water. The maximum conductivity of the deionized water used for this purpose must only be a 5 μs/cm. The water and ice is mixed so that the water level in the vessel is approximately one-half inch below the ice surface. The water level should be checked regularly while calibrating and any excessive water removed using a hand pump and replaced by ice. This allows the ice point to be shown as 32°F (0°C) ± -5 mK.

Cold junction compensation in thermostats

Cold junction can also be tempered in a stable liquid bath or Peltier thermostats. If the cold junction temperature deviates from the reference temperature of the basic series of thermocouple measurements, the measured thermal voltage has to be corrected accordingly (see Section 2.7.2.7). To be on the safe side the temperature in thermostats is monitored with a calibrated thermometer. Typical ice point uncertainty is 32°F (0°C) ± 10 mK.

Cold junction compensation in triple-point

If no other tempering unit is available, the water triple-point can also serve for tempering one to two thermocouple cold junctions. Approximately 3 to 5 ml alcohol should be added to the inner tube of the cell to improve the heat conductivity. The 0.01 K error produced by the difference between triple-point and ice point temperature can be ignored.

Recording measured values

Frequently calibrated or validated RtRh-Pt thermocouples, Model S or R are often used as standards when calibrating with dry block calibrators. Appropriate tables and equations are given in the calibration or validation certificate to convert the thermal voltage into a temperature. The thermal legs of the (standard) element are drawn into a ceramic two-bore capillary which is put in a ceramic protective tube, for example, Type 710 with an outer diameter of 7 mm and length of 500 mm. Specimens and standards are put in the as far as possible. Their thermal junctions (measuring points) should be at the same installation depth to keep the error through vertical gradients small. The opening in the dry block calibrator is closed-off with mineral wool. The measured values are recorded after a stable temperature is reached. The following cycle can be carried out with the manual or automatic scanner:

$$U_N - U_1 - U_2 - ... - U_n - U_N - U_n - ... - U_2 - U_1 - U_N$$

$$(3-19)$$

U_N is the thermal voltage of the standard and U_1 -U_2 - .... U_n are the specimens. The intervals in time between the two measurements should always be the same. It is assumed that the temperature in the oven changes almost linearly within a short period of time. At least three measuring cycles are carried out at each testing temperature. The error due to temperature fluctuations during one measuring cycle, which can be 10 times greater compared with liquid baths, is minimized by taking the mean value of the different measurements.

Thermal electromotive force is measured, for example, by a high-resolution digital multimeter (DMM). By changing the connections on the DMM before and after measuring you should check whether parasitic thermo-electromotive forces or galvanic elements cause measurement errors. This should be considered where necessary by averaging the measured values.

Calibration in temperature block calibrators

When calibrating a thermometer in a temperature block calibrator the temperature displayed or its output signal is directly compared with the calibrated display of the temperature block calibrator. Portable calibrators are a very simple way of calibrating contact thermometers, and even measuring chains with electrical thermometers, measurement transducers, cable and evaluation units can be calibrated quickly. The calibrators include a thermally insulated metal block which can be heated (or cooled in the case of instruments working with Peltier elements). The standard is installed directly in the metal block and is calibrated with a second standard, which is also provided in the block for this purpose. The working range of the typical commercial temperature calibrators using a Pt resistance thermometer as the standard is from approx. -10°F to 1200°F. Calibrators using Peltier elements are typically used from -13°F to 300°F. Those equipped with a resistance heating system work from 95°F to 1200°F (Figure 3.32).

Just like dry block calibrators, temperature calibrators have aluminum, brass or bronze inserts with the necessary test holes, which are drilled to the diameter of the specimens. What was addressed for dry block calibrator inserts with respect to hole diameter and air gap is also applicable in this case. Unlike the dry block calibrator, however, only one or two thermometers can be calibrated at once in temperature calibrators as a rule due to the difference in size of the inserts depending on diameter. Considerably less time is required, however, due to the reduced thermal mass of the heating block.

Figure 3.32   Temperature dry block calibrator, Model 9123

Differences in temperature between the specimen in the insert and the installed standard falsify the calibration result to a minimal degree because these differences have already been considered during the calibration of the calibrator, i.e. calibrated with the system. However, this is subject to the specimens always being fully inserted down to the base in the calibrator and being similar in design to the standard used when calibrating the instrument. Temperature fluctuations over a period of 30 minutes amount to $\pm$ 0.02 K to 400°F and $\pm$ 0.05 K to 1100°F, for example (WIKA Model 9123). Fully considering the factors which falsify calibration, the total measurement uncertainties for cali-

brating in the temperature calibrator Model 9123 can be given as $\pm$ 0.2 K up to 400°F and $\pm$ 0.1% above 400°F of the testing temperature (subject to stable specimens).

3.2.3.3 Error observations for thermometer calibrating

In the following error observations the uncertainty of measurement according to the procedure described in Section 3.2.1.3 is determined from the given determining factors for two typical calibrating operations.

Calibrating resistance thermometers

A precision Pt resistance thermometer was calibrated by comparing it with a standard thermometer in an agitated liquid bath at 212°F using silicone oil as tempering fluid. The measured values of the specimen and standard were recorded as a series of measurements (n=20 measurements). The uncertainty of measurement u = $\pm$ 2 mK of the standard is taken from its calibration certificate and respectively converted with Gl 3.15. The error from inhomogeneous temperature distribution and temporal fluctuations were determined by experiment when evaluating the bath (see Section 3.2.3.2). The evaluation of the resistance between the initial and final measurement of the specimen at the water triple-point was chosen here as measurement for the short term stability and converted into mK.

Source of error	i	a_i in mK	a_i^2 in mK²	S_{xi}^2 in mK²	Remarks
Standard	1	-	-	1	to eq. 3-17
Spatial temperature distribution in bath	2	4	16	5.3	to eq. 3-15
Temporal temperature distribution in bath	3	-	-	3.2	experimental
Resistance measurement of standard	4	4	16	3.2	to eq. 3-15
-Random error, resistance measurement	5	-	-	0.8	to eq. 3-11, 3-12
Resistance measurement of specimen	6	1	1	0.3	to eq. 3-15
-Random error, resistance measurement	7	-	-	0 .1	to eq. 3-11, 3-12
Short term stability of specimen	8	10	100	33.3	to eq. 3-15
Resulting variance, Sy^2 in mK²				47.2	to eq. 3-16
Resulting standard deviation, Sy in mK				6.9	
Total uncertainty of measurement, $\pm$ u in mK (k = 2)				13.9	to eq. 3-17

Table 3.13 Uncertainty of measurement when calibrating resistance thermometers in liquid baths at 212°F (100° C)

Source of error	i	a_i in K	a_i^2 in K²	S_{xi}^2 in K²	Remarks
Standard, Type S thermocouple	1	2	4	1.333	to eq. 3-15
Temperature difference between two specimen holes	2	0.5	0.25	0.083	to eq. 3-15
Temporal fluctuations in oven insert	3	-	-	0.050	experimental
Thermal voltage measurement of standard	4	0.032	0.0010	0.0003	to eq. 3-15
-Random error, thermal voltage measurement	5	-	-	0.050	to eq. 3-11, 3-12
Thermal voltage measurement of specimen	6	0.016	0.0003	0.001	to eq. 3-15
-Random error, thermal voltage measurement	7	-	-	0.013	to eq. 3-11, 3-12
Error caused by cold junction compensation	8	0.10	0.01	0.003	to eq. 3-15
Short term stability of specimen[1]	9	1	1	0.333	to eq. 3-15
Resulting variance, Sy^2 in K²				1.9	to eq. 3-16
Resulting standard deviation, Sy in K				1.4	
Total uncertainty of measurement, $\pm$ u in K (k = 2)			2.8	to eq. 3-17	

[1] estimated, based on experience gained with previous measurements

Table 3.14 Uncertainty of measurement when calibrating thermocouples in a tube furnance at 1800° F (1000°C)

Calibrating thermocouples

Type K thermocouples were calibrated in the dry block calibrator at 1800°F. A calibrated Type S thermocouple, calibration error limit $\pm$ 2 K, was used as a standard. The characteristic data for the oven as well as for the digital multimeter used are known from calibration and data sheets. The calibrating results are available as a series of measurements, n = 20.

3.2.4 Calibrating result documentation

The **calibration certificate** shows the calibration results and documents the traceability of the calibration to national standards. The calibration information is documented on the certificate. This includes a brief description of the object calibrated, the calibration method used including information on the standards and measuring facilities used as well as the ambient conditions relevant for the calibration.
Complete details of the measurement results include the value of the measurement, the displayed value, the deviation in measurement and the total uncertainty of measurement. Conformity statements can be added, for example, that the deviation in measurement remains within a certain tolerance class.
After calibrating, the calibrated object is labeled with a calibration number that is shown on all pages of the calibration certificate.

3.3 Electromagnetic compatibility

Electromagnetic compatibility or **EMC** for short, has become a prominant subject in recent years in electric measuring technology. There is great uncertainty about this subject, particularly due to pressure to introduce the **"CE symbol"** in the electronic measuring industry that became mandatory after 1996, which calls for a number of different standards and regulations to be observed.

3.3.1 Basic physical definitions

3.3.1.1 Basic definition of EMC

Electromagnetic compatibility in the general sense means that

a) the equipment is not damaged in function, or only to a limited, defined extent, by external electromagnetic interference energy up to a defined maximum value which gets into the equipment by any possible way, i.e. radiation, through connection cables, or through the instrument housing (**susceptibility**). Permanent damage or interference must not occur.

b) the equipment emits so little electromagnetic interference energy by any possible way, i.e. radiation or by cables (**emission**), so that other equipment performing a) is not destroyed.

For better measurement and description of the processes and origin, a differentiation is made physically and technically between different forms of interference energy and the transmission paths. These differences have ultimately found their way into the different standards and laws. A combination of these different forms of interference always occurs in practice because the forms of interference can be physically converted into each other. In other words: voltage interference can always be transformed or converted into a current interference or into a free electromagnetic wave. Broad band interference, a pulse with a broad frequency spectrum, can arise from a narrow band interference, which is, for example, a sinusoidal wave with fixed frequency in the case of electronic circuits.

3.3.1.2 Voltage interference

Voltage interferences are voltage fluctuations in a frequency range from 0 Hz to several GHz, which can penetrate into the equipment through the housing and supply lines. Voltage disturbances spread galvanically via the lines or through capacitances in the circuit. This can be viewed as a battery or an **interference voltage generator** connected between two points in the circuit which can also be the housing, supply lines or the ground.
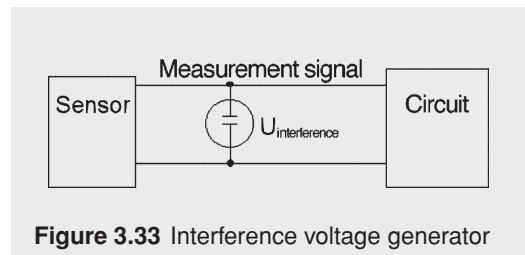
Figure 3.33 Interference voltage generator

3.3.1.3 Current interference

Current interferences are current fluctuations with frequencies from 0 Hz up to several GHz, which can penetrate through the supply lines and the housing into the equipment. Current interferences spread along the circuit galvanically through the lines or through magnetically coupled inductances, which can be parallel lines or transformers. This can be viewed as splitting an imaginary line and inserting an **interference current generator** at that point.
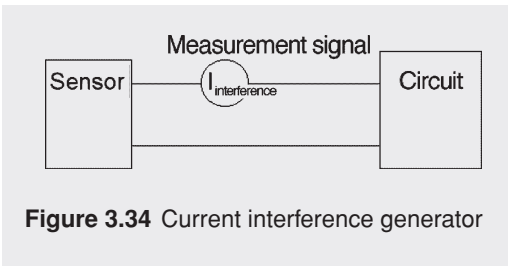
Figure 3.34 Current interference generator

3.3.1.4 Electromagnetic waves

A third type of interference is the **electromagnetic wave** which spreads through space. These waves are also called **radiation fields**. In this case the equipment with its spatial line geometry acts as transmitter and receiver at the same time. Finally the electromagnetic energy on the components transforms into voltage or current interference which disturbs the equipments function or destroys it.

Frequency ranges of electromagnetic waves

Interference electromagnetic waves exist from the lowest (up to a defined maximum value 0.1 Hz) to the highest (several GHz) frequencies.

The **interference range** is strongly influenced by the frequency or radiation capacity and coupling possibility, which is likewise determined by the frequency.

0.1 Hz to 10 kHz:
The interference radiation with voltage component extends only a few tenths to a half of an inch into free space. Only the 50/60 Hz "hum" of the overhead power lines via the magnetic components is a real source of interference.

10 KHz to 30 MHz:
These are radio frequencies in the long wave to short wave range. The interference range, depending on frequency and transmitter capacity, extends from just a few half inches to well over 100 miles.

Interference in this frequency range spreads mainly by conductance. However, the proportion of interference radiation grows greatly towards 30 MHz. The most frequent interferences in this frequency range have an interference radius of up to several hundred yards around the interference transmitter.

30 MHz to 500 MHz:
This is the ultra short wave range up to televison frequencies. Interference spreads mainly by radiation. Interference ranges of up to several hundred miles occur.

500 MHz to several GHz:
This is the frequency range for satellite radio and relay radio. Interference spreads primarily by radiation with ranges of up to 10 yards.

3.3.1.5 Types of coupling for electromagnetic interference

Physical couplings

There are three different types of physical couplings. Electromagnetic waves can induce interference currents in other lines and circuits through magnetic field coupling of lines (inductive coupling). They can also generate interference voltages through the electric field coupling of lines (capacitive coupling) in other lines and circuits. Free field propagation in space allows electromagnetic waves to generate interference voltages and interference currents (**field coupling**) in the spatial line geometry.

Normal mode and common-mode interference

Normal mode interference is described as symmetrical or asymmetrical coupling depending on the type of coupling.

In **symmetrical coupling** the interference current flows on one conductor to the equipment and back on the other so that a closed current circuit is

formed. If in this case the system is not grounded, it is called symmetrical interference. The term normal mode interference is also used because the currents on the **connection lines flow** in normal mode. Normal mode interference is superimposed on the useful signal and thus leads to measurement errors and functional disturbances.

In **unsymmetrical coupling** the same principle applies. However, in this case the system is grounded on one side.

Figure 3.35 Unsymmetrical interference coupling
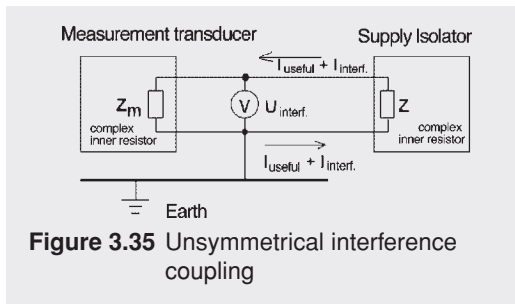
Common-mode interference is also described as **asymmetrical coupling**.
In an asymmetrical coupling the interference signal is fed between ground and the connection lines so that the interference current flows in parallel via the connection lines into the equipment and back via parasite capacitances between the circuit, housing and ground. This is called normal mode interference because the connection lines are in normal mode. Normal mode interference does not necessarily lead to interference in the circuit because it cancels itself to a large extent. Unsymmetrical capacitances to ground, for example through the printed circuit board layout, are needed before a normal mode signal is trans-

formed partly into a common mode signal, which then causes interference. This conversion is called **normal-mode common-mode conversion**.

Figure 3.36 Asymmetrical interference coupling
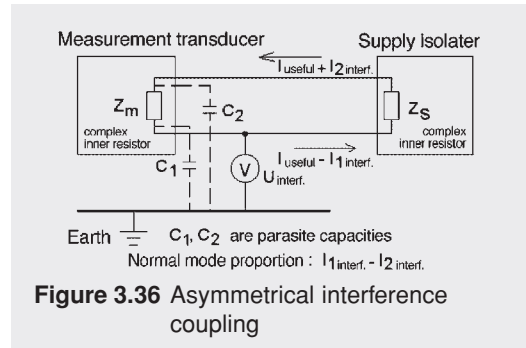
Substitute models for electromagnetic interference.
To record the course of electromagnetic interference in measuring technology and to be able to describe it, the interference sources are idealized into voltage and current sources.

Voltage sources are voltage generators with a low or high internal impedance. This can be demonstrated by a battery with a series resistor.

Current sources are current generators generally with a low internal impedance. An example is the transformer, whose low-resistance secondary winding is installed in a connection line.

3.3.2 EMC standards and regulations

The following standards are valid in Germany:

The **generic standards for EMC** in Germany and Europe (Table 3.15).

GENERIC STANDARD	Basic standard	valid as from	Type of interference
EN 50 082, part 1	VDE 0839, part 82-1	3/93	Interference immunity
EN 50 081, part 1	VDE 0839, part 81-1	3/93	Emitted interference
EN 50 082, part 2	VDE 0839, part 82-2	still being considered	Interference immunity
EN 50 081, part 2	VDE 0839, part 81-2	still being considered	Emitted interference
Table 3.15 The generic standards for EMC			

The **product standards for EMC** in Germany and Europe
(Table 3.16).

Equipment class	Emitted interference	Interference immunity
ISM equipment (living area, business and trade sector, small industry)	EN 55011 Radio interference of equipment for ISM purposes	(EN 50082-1) Generic standard
Industrial sector	EN 50081-2 Industrial sector	EN 50082-2 Generic standard
Household appliances	EN 55015 Electrical household appliances, electric hand tools	(EN 50082-1) Generic standard
Radio and television receivers	EN 55013 Radio receivers and connected equipment	EN 55020 Interference immunity of radio and television receivers
Fluorescent lamps and lighting fixtures	EN 55015 Emitted interference of fluorescent lamps and lighting fixture	(EN 55082-1) Generic standard
Technical information equipment	EN 55022 Radio interference of ITE	prEN55101 EN55024 in planning
Defects in current supply networks	EN 60555-1 Definitions EN 60555-2 Harmonic oscillations EN 60555-3 Voltage fluctuations	
Table 3.16 The EMC product standards		

Measuring method (BASIC STANDARDS) for EMC in Germany and Europe (Table 3.17).

Standard	Content	Norm
	Overview	IEC 77B (Co) 4
EN61000-4-01	Definitions	IEC 801-1
EN61000-4-02	ESD (Electrostatic discharge)	IEC 801-2
EN61000-4-03	High frequency fields	IEC 801-3
EN61000-4-04	Burst	IEC 801-4
EN61000-4-05	Surge	IEC 801-5
EN61000-4-06	High frequency (HF) interference by conduction	IEC 81-6
EN61000-4-08	Magnetic fields 50/60Hz	IEC 77B (Sec) 72
EN61000-4-11	Mains failure, voltage variation	DS 5104
EN61000-4-16	Conducted low frequency	IEC 77A/120/CD
EN61000-4-12	Dampened oscillations	IEC 77B (Sec) 73
EN61000-4-09	Magnetic fields, pulse	IEC 77B (Sec) 72
EN61000-4-10	Magnetic fields from oscillations (H field of dampened oscillations)	IEC 77B (Sec) 73
Table 3.17 EMC measuring methods		

3.3.3 Breakdown of measuring methods by defined interference

3.3.3.1 Radiated field

For a long time, radio transmitters of all kinds such as radio and television transmitters, taxi and amateur radio and the walkie-talkies for emergency personnel have been sources of radiated fields. Any devices that generate electrical sparks such as DC electric motors are also potential sources of interference. In more recent times, overhead power lines and computers with high cycle frequencies in particular have become additional new sources of interference. The first practical tests for direct radiated fields were mostly carried out on the walkie-talkie units used in factories. These testing methods were tailored to the specific applications, and as a rule the results could only be applied to other applications with reservations.

Comparable and repeatable measurements of interference behavior in a radiated field became mandatory with the coming of EMC legislation. Explicit discussions as to what constitutes a realistic comparable measurement are still ongoing.

The aim is to determine the "pure" interference behavior of the equipment when subjected to a defined electromagnetic interference field strength and direction without additional secondary effects through other types of interferences. In the case of electromagnetic fields in particular, a test specimen is never non-interacting with its surrounding field; this and the existence of other sources of interference such as radio transmitters, have prompted the successive development of a number of measuring methods to get closer to this goal at acceptable expense.

The oldest method, which for a long time was considered to be the best, is **free field measurement**. A transmitter antenna is set-up outdoors and the specimen is put into operation in the same way as in real use. Different frequencies from 30MHz to 1 GHz are then radiated in steps onto the device which is tested for interference and measurement error.

Problems occur with the precise regulation of the real field strength and its direction over all frequencies. Interference fields coming from the outside cannot be shielded; they can only be eliminated by calculation. Even small alterations in the structure of the specimen can generate a drastic change in the measurement. Furthermore, the influence of weather conditions can result in poor system availability and considerably increase operator and plant costs.

Free field measurement problems have been reduced to some extent by halls or large chambers that are completely shielded from the outside and furnished with absorbers on the inside so that an ideal free field can be built up on their inside. Otherwise the internal measurement set-up is the same as when taking free field measurements.

Problems in this respect are ideal fields that are only approximately ideal and which, in large specimens, become more and more a matter of chance and specimen structure. Moreover the investment costs are enormously high. Nevertheless, better availability and repeatability of this technology means it is likely to replace free field measurement as the standard.

TEM cells (**T**ransversal **E**lectromagnetic **C**ells) have been developed for small specimens such as transmitters due to the extremely high costs for **absorber halls**. These cells, 1 to 2 yards in size, are basically a large capacitor in which the homogeneous field of the specimen is tested. Such a plant is more favorable in price by comparison but it is only appropriate for small specimens. Only single components can be tested, not a complete switch cabinet. The results are transferrable to measurements in absorber halls only to a certain extent. As a result, TEM cells are appropriate primarily for product development pre-trials but not for approvals. Further developments in this technology are **GTEM cells**. In this case a homoge-

neous field is not generated with a parallel plate capacitor, but rather the capacitor plates form an **acute angle** to each other. The high frequency is fed into the intersection of the plates. Transversal electromagnetic waves are generated, which move to the open end of the delta formed by the plates. The open end is closed by graphite so that no reflections occur. GTEM cells are suitable for higher frequencies than TEM cells. There is less reflection and they can also be used for emission measurements.

3.3.3.2 Bursts

When larger currents are switched with inductances, and particularly when the current circuit is interrupted rapidly, repeating high-power voltage peaks occur with peak values of more than 4 kW. This phenomenon is called **bursting**. Interference frequencies in the range of 5 kHz up to 200 MHz are generated in such cases. Bursts spread over the lines and capacitively over the case and the neighboring lines. Burst interferences have become particularly frequent with the appearance of more powerful electric motors, compressors and similar equipment. Semi-conductor elements can be destroyed or circuits disturbed because of the fast, high increase in voltage. In this case, the single pulse is not very rich in energy, but the voltage is particularly destructive.

Fast interference pulses lasting some 50 ns are generated (1st Drawing, Figure 3.37) for adequate simulation of the wide frequency range of the bursts. These are repeated in groups of approx. 15 ms in duration (see Figure 3.37), and the groups are repeated every 300 ms. These pulses are coupled capacitively via capacitors or by means of a 1 m long **coupling clamp** to the specimen connecting line. The peak voltage value varies between 1 kV and 4 kV depending on the severity of the test.
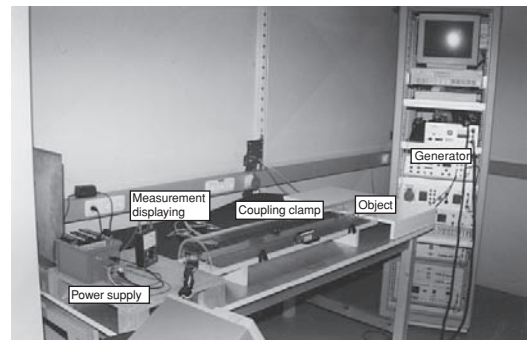
Figure 3.38 Measuring system with coupling clamp
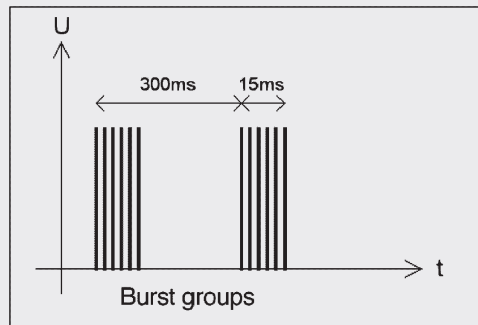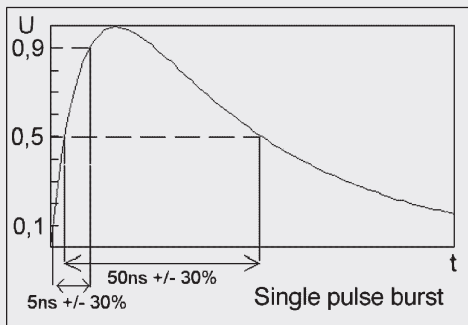
Figure 3.37 Standard burst pulses

3.3.3.3 ESD

Electro**s**tatic **d**ischarge (ESD) is the electrostatic discharge from a human body which has been charged statically through friction electricity on carpets, couches or clothing. In such a case, the human body can be charged from 10 kV to 40 kV. If a statically charged person comes close to an grounded conductor an arc discharge may occur. Discharging can also take place through direct contact. Such sparkovers are frequently destructive; the least they do is interfere with the function of electronic components and especially semiconductors and integrated circuits. Peak currents of up to 60 A are possible! As a result a piece of equipment used in industry must be protected against ESD, otherwise breakdowns and damage will rise.

The human being is replaced by an electronic circuit for test purposes and reproducible measurements (Figure 3.39). A capacitor is selected for this circuit, which is called a **human model** and which is charged with a high resistance and discharged with a low resistance via a relay.
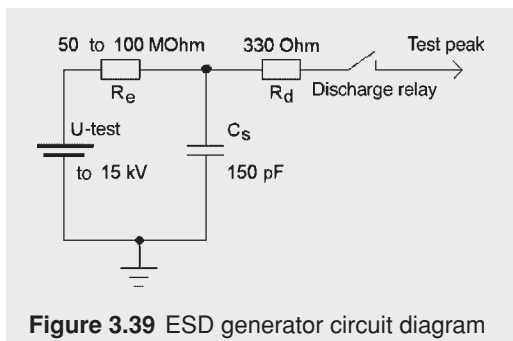
Figure 3.39 ESD generator circuit diagram

Two methods are used with voltages up to 15 kV and the tested device in operational state:

a) The test generator is applied to all parts of a piece of equipment accessible to a human finger from the outside. Then, by closing the relay, the capacitor C_s is discharged via the resistor R_d and via the equipment (**contact discharging**). Ten dis-

charges are applied to each contact point at a selected fixed test voltage.

b) The test generator with a closed relay contact is brought up close to all these parts accessible to a human finger from the outside. The capacitor C_s is discharged by arcing through the resistor R_d and through the equipment (**contactless discharge**). Here again ten discharges were applied to each point. Figure 3.40 shows the experimental set-up for ESD tests.
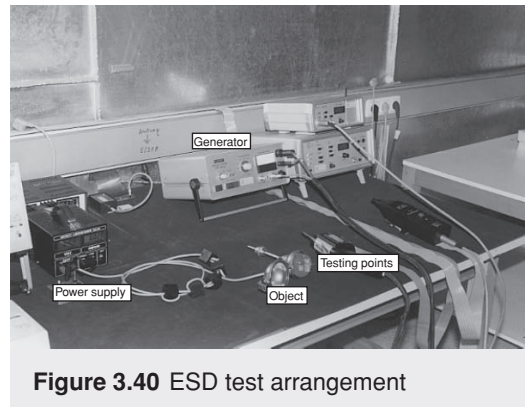
Figure 3.40 ESD test arrangement

3.3.3.4 Surge

Lightning striking close to power supply network lines can cause interference or lasting damage to the consumers although the lightning does not directly strike the line network.
The cause of damage and interference is the very high energy current in the line network which is induced by the lightning. These secondary current and voltage interferences are called **surge** currents. The currents of up to 200 kA directly existing in the lightning channel are not considered here.

The more frequent phenomenon of induced surge interference is the subject of the test considered here. The standard test copies the current and voltage pulses occurring in the real world.
The standard test generator generates single interference pulses which at up to 4 kV and 100 A

are significantly higher in energy than the interference pulses from ESD and bursting. For this purpose use is made of a combination generator as shown in Figure 3.41, which can generate two types of pulses:

a) A **voltage pulse in idling operation for lightning simulation** when testing insulation in accordance with Figure 3.42.

b) A **current pulse in short circuit operation for energy testing of protective elements** in accordance with Figure 3.43.
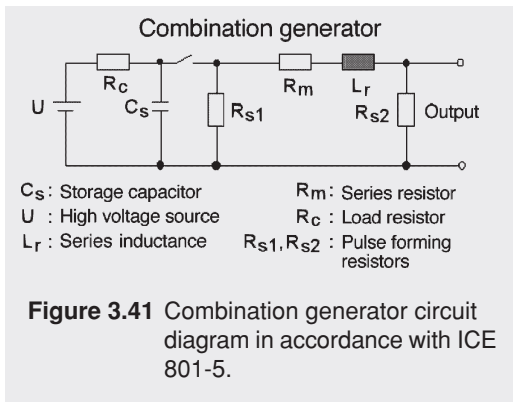
Figure 3.41 Combination generator circuit diagram in accordance with ICE 801-5.
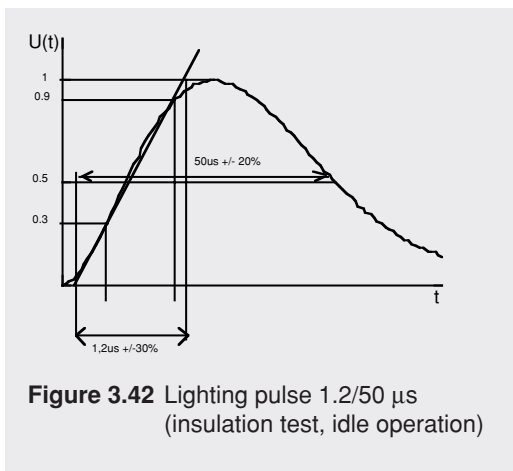
Figure 3.42 Lighting pulse 1.2/50 µs (insulation test, idle operation)
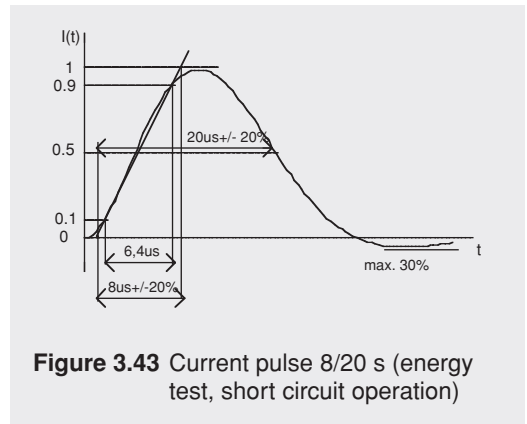
Figure 3.43 Current pulse 8/20 s (energy test, short circuit operation)

Depending upon the purpose of the test and the specimen, the energy is coupled galvanically, capacitively, inductively and as radiated pulse. The actual purpose of the test is always the simulation of possible lightning interference depending on location.

3.3.3.5 Voltage interruption/voltage fluctuation

Voltage interruptions can occur for a short time, up to approx. 20 ms, in the overhead power supply as a result of load changes of other consumers. After a power failure, overvoltages frequently occur in the ms range of up to 3 times the nominal value. An appliance supplied from the overhead voltage must not be damaged under these conditions. Irregularities in function in the case of a breakdown in the overhead power supply longer than 20 ms are also to be tolerated. Permanent irregularities in function must not occur.

Long-term voltage fluctuations in a range of less than 1 sec. up to several hours are generated in the overhead power supply network under average consumer load. Fluctuations up to10% of the voltage occur in the overhead power and even up to -15% for approx. 0.5 s in the short term. Equipment using power from the overhead power supply must work within a specified tolerance range without fault due to such voltage fluctuations.

3.3.3.6 Conducted high frequency irregularities

In test measurements with radiated field (see Section 3.3) the measured values are spread over a range of 150 kHz to 80 MHz depending on the testing equipment. **Coupling to the supply lines** and to the specimen in particular has a great influence on the results. The physical background is partly the fact that in the case of these frequences the so-called **near field** of the transmitter antenna is connected to the specimen supply lines. In this case the distance of the specimen, which is 10 to 30 feet from the transmitting antenna, is smaller or equal to the wavelength of the electromagnetic wave at 2 to 4 miles. The results are reproducible when the high frequency is directly coupled capacitively or inductively to the connection lines. In reality numerous directly generated or connected interference voltages exist in these frequency ranges, particularly in the power supply network. They are supplied mainly through efficiently shielded consumers with switching power packs in the power supply network. Computers are the cause of a large proportion of this type of interference. The **ripple control systems** of the electricity boards, which switch the meters on consumers in a frequency range of several kHz with a capacity in the short wave range, likewise generate interference.

Shown in Figure 3.44 is the experimental setup for testing conducted high frequency interference. Narrow-band (single) frequencies from 150 kHz to 80 MHz are measured for selective recognition of the reaction of the appliances. Unmodulated or tone-modulated high frequency at 1 kHz/80% is fed to the supply lines. Depending on the severity of the test they are carried out at an amplitude of 1 V to 10 V or at an amplitude of 30 V for a higher degree of severity. The high frequency is generated by a generator adjustable over a range of 150 kHz to 80 MHz. Two generators can also be used, one from 150 kHz to 30 MHz and a second from 30 MHz to 80 MHz. In special cases where supply lines are short and appliances are geometrically small, the tests can also be carried

out with frequencies up to max. 230 MHz by special agreement.
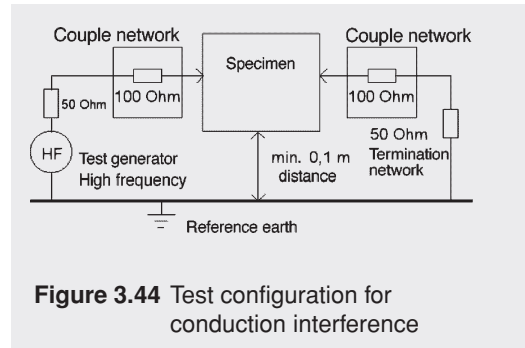
Figure 3.44 Test configuration for conduction interference

The unit under test is fully operational during the test. Deviations in measurement from the desired measured value are accepted as long as they are within the specified basic tolerance.

3.3.3.7 Overhead power frequency interference (hum)

While the overhead power frequency in Germany and Europe is 50 Hz, in the USA it is 60 Hz. Since the supply lines form large induction loops, a magnetic interference field with a frequency of 50/60 Hz exists almost all the time. As a result this type of interference was one of the first to be measured.

a) A common mode or symmetrical interference voltage of 250 VAC (effective) with 50/60 Hz is connected up between the line connections and the ground (see Section 3.3 and Figure 3.35). This assumes that the line connections are ground-free and the specimen is fully operational. The input source must be free of interference.
b) A serial or asymmetrical interference voltage with a peak value smaller or equal to 1 VAC with 50/60 Hz is connected up in the measuring line. The measurement set-up used can be seen in Figure 3.45. The measurement must be taken at 10% and 90% of the measurement voltage. The

worst case value is then sought for the interference voltage phase. If the measured error is less than 0.5% of the measuring voltage with an interference voltage peak value of 1 VAC, this value must be quoted. In other cases the interference voltage at which the measurement error amounts to 0.5% of the measuring voltage is to be specified.
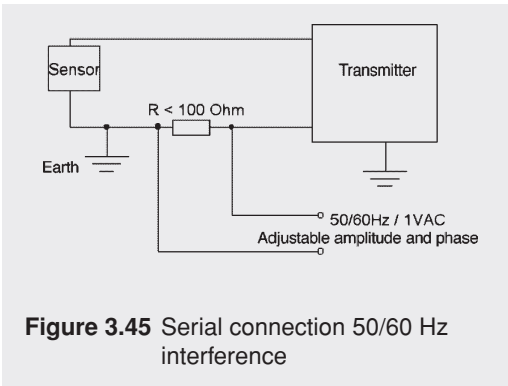
Figure 3.45 Serial connection 50/60 Hz interference

3.3.3.8 Residual ripple

After conversion of alternate current into direct current with a transfomer, there is a **residual ripple** of 50 Hz or a multiple of this, superimposed on the direct current. This accounts for 10% of the direct current a poor transformer and causes obvious errors in measurement, particularly in the current loop (4 mA to 20 mA).

The test measures the reaction of the equipment to residual sections of the overhead power alternating current as well as their multiples, mainly 100 Hz. The current loop supply voltage is superimposed thereby to 10% with alternate current. The equipment funtions normally during the test. Measurements are taken at 10%, 50% and 90% of the loop current. The current error peak value must not be greater than 3% of the measuring voltage, i.e. 48 μA.

3.3.3.9 Emitted interference radiation

Active electronic equipment, particularly equipment with microprocessors but also digital transmitters or computers, generate high frequency interference voltages internally due to oscillators and switching flanks which are radiated through connection lines and housings.

Measurements are taken in a free field or in absorber halls with reception antennas. The field strength and the direction of the 10 kHz to 1 GHz frequencies emitted by the specimen are measured by decade at a distance of 10 to 30 feet from the specimen, respectively.

3.3.4 Demands on equipment behavior in industry

The demands on equipment in respect of its reaction interference depend on the range of application. Moreover, all the inputs and outputs on the equipment are not considered in the same way but the different interfaces of a piece of equipment are weighted according to technical significance and function. Where an overhead voltage supply is concerned it does not matter whether 100 Hz interference voltages are superimposed, but it certainly does matter in the case of current loops. The respective type of interference and magnitude of interference or interference energy is determined separately for each interface.

3.3.4.1 Equipment behavior classification when exposed to interference

The behavior of equipment under an interference load is evaluated according to three different categories of behavior when taking measurements:

Category A: The equipment keeps within the specified measurement accuracy. Frequently this is understood to be also the basic accuracy (see also Section 3.3.4.3).

Category B: Under the interference load the equipment is subject to irregularities in function but recovers on its own after the interference load has ended.

Category C: The equipment is subject to functional disturbances when exposed to an interference load and must be put into operation again by the operator.

Depending on the type of equipment, interference magnitude, type of approval and interface concerned, the specimen must comply with a minimum category for approval.

No.	Title	EG directive	Transformation into German Law	Application possible as from	Application mandatory as from
1	Simple pressure tanks	87/404/EWG	GSG 6.GSGV	01.07.1991	01.07.1992
2	Toy safety	88/378/EWG	GSG 2.GSGV		01.01.1991
3	Building products	89/106/EWG	Building Product Law		01.06.1991
4	Electromagnetic compatibility	89/336/EWG	EMV Law	01.01.1992	01.01.1996
5	Machines	89/392/EWG	GSG 9.GSGV	01.01.1993	01.01.1995
6	Personal protection equipment	89/686/EWG	GSG 8.GSGV	01.07.1992	01.01.1995
7	Non-automatic weighers	90/384/EWG	Calibration Ordinance	01.01.1993	01.01.2003
8	Active implantable medical equipment	90/385/EWG	Medical Product Law	01.01.1993	01.01.1995
9	Gas consumption facilities	90/386/EWG	GSG 7.GSGV	01.01.1992	01.01.1996
10	Telecommunication terminals	91/263/EWG	Post office Approval Ordinance		01.11.1992
11	New hot water boilers with liquid or gaseous fuels	92/042/EWG	still open	01.01.1994	01.01.1998
12	Electrical equipment for use within certain voltage limits (low voltage directive)	73/023/EWG	GSG 1.GSGV	01.01.1995	01.01.1997
13	Medical products	93/042/EWG	Medical Product Law	01.01.1995	01.01.1998 01.07.2004
14	Equipment and protection systems in explosion-hazardous area	94/009/EG	still open	01.03.1996	01.07.2003

Table 3.18 Introduction dates for CE symbol

3.3.4.2 The CE symbol

The CE conformity symbol, known in brief as CE symbol, is or will become mandatory for all products within Europe and possibly the U.S. As a manufacturer's declaration it certifies that the product in question fulfils all EC (European Community) specifications and standards valid for the particular class of equipment. This applies to EMC as well as to the design or safety regulations and approvals for all products, whether transmitter, toy or production machine. Introduction dates have been set for the respective type of product (see Table 3.18).

Moreover the CE conformity symbol stipulates mandatory documentation and symbol for these products.

The transition period ends on the first of January 1996 particularly in the EMC sector. From then on, all equipment delivered must comply with the re-

quired resistance to interference and interference radiation safety. For equipment which fails to observe these standards, the deviations from the standard must be documented from case to case or delivery is strictly prohibited.

The following table 3.19 shows industrial requirements which are still in discussion to some extent:

Interface	Type of interference	Measurement standard	Interference magnitude	Required behaviour under interf. load
Housing	ISD radiated field pulse field 900MHz magnetic field 50Hz	IEC 801-2 IEC 801-3 ENV 50141 IEC 1000-4-8	6 kV [1] /8 kV [2] 10 V/m 10 V/m 1 A/m only for monitors	B A A A
AC citypower supply	Voltage interruption Voltage fluctuation Voltage fluctuation Burst Surge HF on line	IEC 77B (CO)17 IEC 77B (CO)17 IEC 77B (CO)17 IEC 801-4 IEC 801-5 IEC 801-6	5 s > 95% 10 ms / 30% 100 ms / 50% 2 kV 1 kV / 2 kV 10 V	C B C B B A
DC supply	Burst Surge HF on line	IEC 801-4 IEC 801-5 IEC 801-6	2 kV 0,5 kV / 1 kV 10 V	B B A
Signal inputs Signal outputs Signal lines	Burst HF on line	IEC 801-4 IEC 801-6	1 kV 10 V	B A

Table 3.19 EMC CE symbol requirements (industry)

[1] direct contact, [2] through air

Interface	Type of interference	Measurement standard	Interference magnitude normal requirement	Interference magnitude higher requirement	Required behaviour under inter-ference load
Housing	ISD	IEC 801-2	6 kV [1] / 8 kV [2]	8 kV [1] / 15 kV [2]	A
	Radiated field	IEC 801-3	10 V/m	30 V/m	A
	Pulse field 900MHz	ENV 50141	10 V/m	30 V/m	A
	Magnetic field 50Hz	IEC 1000-4-8	1 A/m only for monitors		A
AC mains power supply	Voltage interruption	IEC 77B (CO)17	5 s > 95%	5 s > 95%	C
	Voltage fluctuation	IEC 77B (CO)17	10 ms / 30%	10 ms / 30%	B
	Voltage fluctuation	IEC 77B (CO)17	100 ms / 50%	100 ms / 50%	C
	Burst	IEC 801-4	2 kV	4 kV	A
	Surge	IEC 801-5	1 kV / 2 kV	2 kV / 4 kV	B
	HF on line	IEC 801-6	10 V	30 V	A
	Frequency tolerance (50/60 Hz)	DIN VDE 160	± 2%	± 6%	A
DC supply	Burst	IEC 801-4	2 kV	4 kV	A
	Surge	IEC 801-5	0,5 kV / 1 kV	1 kV	B
	HF on line	IEC 801-6	10 V	30 V	A
Signal input Signal output Signal lines	Burst	IEC 801-4	1 kV	2 kV	A
	HF on line	IEC 801-6	10 V	30 V	A

Table 3.20 EMC requirements according to NAMUR

[1] direct contact, [2] through air

3.4 Explosion protection on electrical measuring devices

3.4.1 Basic terms and definitions

3.4.1.1 Historical development

The mining industry has continuously suffered from explosion accidents since its beginnings in the Middle Ages. It was specifically "fire damp explosions" that brought death to the mines. The cause was pit gas, a mixture of 15% methane with air. The open flames of the pit lamps often ignited the gas mixture until safe lamps with copper gauze were developed by Davy to prevent ignition. Efforts were also made to prevent ignition or explosion with good ventilation of the corridors. With the state of engineering that existed at that time, this method was not effective in most cases. Safer electric lamps and signal systems were introduced around the turn of the century, following the discovery of electricity. Attempts were made to prevent hazardous ignition caused by hot filaments when a bulb broke by armoring and gastight lamps. Nevertheless, accidents continued to happen which were initially difficult to explain.

The concept for integrated safety was developed in Great Britain for signaling in mines from 1914 to 1916. The reason for this development was a serious mine disaster on the 14th October 1913 at Senghenydd in Wales where 439 people died. It was assumed that a spark given off by an electric signal system or a falling rock caused this fire damp explosion.

Subsequent studies revealed that arcing, which occurs in signal switches or bells because of the voltage or inductive energy stored by the bell, could ignite the methane air mixture. At the same time it was also proven that ignition could be prevented by reducing the voltage or restricting the inductive current by ohmic resistors.

This was the beginning of **intrinsic safety explosion protection development**:
the energy which exists at any point in the electric circuit must never be capable of generating ignition sparks, even under faulty conditions.

1917   The first devices based on this general idea were put to use in Great Britain

1936   This principle was also used for the first time outside mining

1945   The first intrinsic safety standard (BS 1259) was issued in Great Britain

1956   This concept was adopted in America

1965   The American Standard RP 12.2 was issued based on this concept.

3.4.1.2 Basic terms of physics

Ignition means that a **mixture of substances**, as a rule a gas mixture, reacts explosively. The combustion of any substances assumes that the reaction components are mixed, i.e. an air-gas mixture in a fire damp explosion or a mixture of dust and air in grain-dust explosions or a liquid-air mixture where gas engines are concerned. Often very low energies are sufficient for ignition and the reactions grow like an avalanche.

The minimum energy needed to start the reaction is called the **ignition energy**. It is determined for each individual substance mixture in a test apparatus. At the present time, an ignition energy of $\leq$ 20 µJ is generally considered harmless for most hazardous substance mixtures.

Types of ignition

An explosive mixture can be physically ignited in different ways. Characteristic for all types of ignition is that the necessary ignition energy can be discharged locally, including by static accumulation over the course of time.

Sparks that can occur when making or breaking a current circuit can generate electric ignition. The direct arcing of high voltages (as are generated, for example, by a spark plug) can also generate sparks.
The connection between two electrical parameters whether it is current, voltage, capacity or inductivity in one power circuit, is shown for a constant ignition probability by the minimum **ignition curve** for a specific ignition mixture (see Figure 3.46).
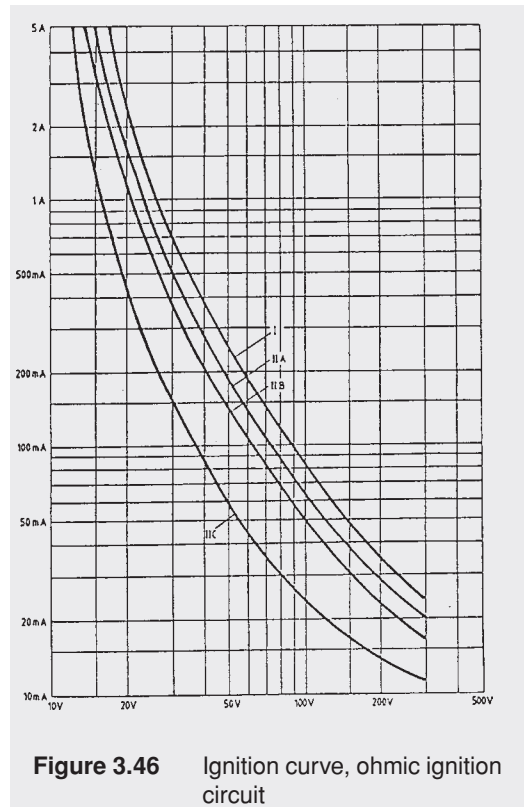
Figure 3.46   Ignition curve, ohmic ignition circuit

Temperature ignition is caused by directly heating the ignition mixture to the necessary reaction temperature. Heating is not performed by **open flames**, however.

The temperature at which the ignition mixture is still capable of being ignited at uniform constant temperature and with the most unfavorable mixture is called the **flashpoint**.

Surface ignition of the ignition mixture occurs on a hot surface even when the ambient temperature is too cold for ignition. Sufficient local static ignition energy exists due to the Maxwell-Boltzmann distribution of energy on the surface. In the event of a fault, this effect can also occur on equipment with surfaces overheated by current. This effect was first considered in the standards after 1964. A flash of lightning can also provide sufficient energy for ignition, as can a reaction-friendly ignition mixture such as oxygen-hydrogen or chlorine-oxygen-hydrogen.

In **pressure wave ignition**, the ignition mixture partner is compressed so strongly by the compression wave that sufficient energy is discharged to ignite the mixture.

Ignition probability is a measurement of the probability that an ignition spark with defined energy will cause ignition. Ignition probability of 0.1% is used as limit condition for the presentation of the minimum ignition curve. Equipment used in explosion hazardous zones must lie below the valid minimum ignition curve by at least the **safety factor** 1.5 even in the case of a fault. This is equivalent to an ignition probability of 1×10^{-6} for such equipment.

3.4.1.3 Standards and regulations

Standards and regulations for instrinsic safety in the United States are defined by the National Fire Protection Association's *National Electrical Code*. (NFPA 70 - Article 500).

In Germany, these standards and regulations are defined by the Physikalische Technische Bundesanstalt (PTB) (Physical and Technical Federal Institute) has sole rights of approval in Germany. It defines and tests new testing methods and publishes the resulting new regulations.

These organizations can be contacted for more complete information than is included in this handbook as follows:

National Fire Protection Association
1 Batterymarch Park
P.O. Box 9101
Quincy, MA 02269-9101 USA

PTB
Physikalische Technische Bundesanstalt
Bundesallee 100
38023 Braunschweig, Germany

Technical characteristic safety parameters for the United States

The NFPA defines harzardous locations by Class, Division, and Group as shown in table 3.47a.

The class defines the state of the combustible material, i.e. gases and vapors, or dust. The division specifies the potential. The group defines the combustable material type.

Class I - Flammable Gases or Vapors	
Division I	• Flammable gases or vapors exist under normal conditions • May exist due to leakage, repair, or maintenance • May be released due to equipment breakdown
Division 2	• Volatile flammable liquids or gases are used, but normally confined in closed containers • Ignitable concentrations are normally prevented by positive mechanical ventilation • Adjacent to a Class I, Division 1 location

Group A: Atmospheres containing Acetylene

Group B: Atmospheres containing hydrogen, fuel and combustible process gases with 30 percent hydrogen, or other equivalent hazardous gases or vapors such as butadiene, ethylene oxide, propylene oxide, and acrolein.

Group C: Atmospheres such as ethyl ether, ethylene, or gases or vapors of equivalent hazard.

Group D: Atmospheres such as acetone, ammonia, benzene, butane, cyclopropanes, ethanol, gasoline, hexanes, methanol, methane, natural gas, propane, or gases or vapors of equivalent hazard.

Table 3.47a   Hazardous Locations Classifications for the United States per NFPA National Electrical Code - Article 500 (1990)

Class II - Combustible Dusts

Division I
- Combustible dusts exist under normal conditions
- May exist due to equipment misuse or breakdown, or due to simultaneous electrical equipment failure
- Electrically conductive dusts may be present

Division 2
- Combustible dusts are not present under normal operation.
- May be produced by equipment breakdown
- Accumulations are sufficient to interfere with the safe dissipation of heat from electrical equipment.
- Accumulations may be ignitable by abnormal or failure of electrical equipment.

Group E: Atmospheres containing combustible metal dusts, including aluminum, magnesium, and their commercial alloys, or other combustible dusts whose particle size, abrasiveness, and conductivity present similar hazards in the use of electrical equipment.

Group F: Atmospheres containing combustible carbonaceous dusts, including carbon black, charcoal, coal, or dusts that have been sensitized by other materials so that they present an explosion hazard.

Group G: Atmospheres containing combustible dusts not included in Group E or F, including flour, grain, wood, plastic, and chemicals.

Class III - Ignitable Fibers or Flyings

Division I   Easily ignitable fibers or materials producing combustible flyings are handled, manufactured, or used.

Division 2   Easily ignitable fibers are stored or handled

Technical characteristic safety parameters for Germany

The equipment must be marked for its specifically approved application and its special connection conditions.
The **ignition group** describes the area of application for which the equipment is approved.
Ignition Group I applies for **mining** for **firedamp hazards**.
Ignition Group II applies for **areas of application outside mining**.

The letters **A**, **B** and **C** for ignition group II also specify the **ignition hazard** of the ignition mixture at ambient temperature and pressure. Classification of the gases is included in the DIN VDE 0165 Standard. The following classifications are valid:

IIA = least hazardous class ignition energy 180 µJ (for example, propane)
IIB = middle class ignition energy 60 µJ (for example, ethylene)
IIC = most hazardous class ignition energy 20 µJ (for example, acetylene or hydrogen)

The **temperature class TX** describes the maximum surface temperature accessible to the ignition mixture, which the equipment must not exceed even under faulty conditions and maximum approved ambient temperature.

T1 = 850°F
T2 = 600°F
T3 = 400°F
T4 = 275°F
T5 = 212°F
T6 = 185°F

Zone grading describes the probability of existence of explosive conditions. Special type and construction regulations can also be valid in the respective zones:

Zone 0 = **Continuous hazard**
explosive gases are present more than 1000 hours/year

Zone 1 = **Occasional hazard**
explosive gases are present between 10 to 1000 hours/year

Zone 2 = **Seldom hazard**
explosive gases are present between **0.1 to 10 hours per year**

Zone 10 = Occasional to continuous hazard
explosive dusts are present more than **10 hours/year**
Zone 11 = Seldom hazard
explosive dusts are present between **0.1 to 10 hours/year**

Safety zone = explosion protection is not necessary.

Electrical signals frequently have to be transmitted from an explosion hazardous zone to a safety zone or into another zone (see Figure 3.47). Moreover, the operating energy must always be transferred from outside into the explosion hazardous zone. The safety zone isolation for the electrical energy is installed in an appropriate piece of equipment as an interface, i.e. in the power supply for a current loop. Special demands are put on such zone isolation so that no energy can get into the critical zone (after Zone 1 or Zone 0) even when a fault occurs.
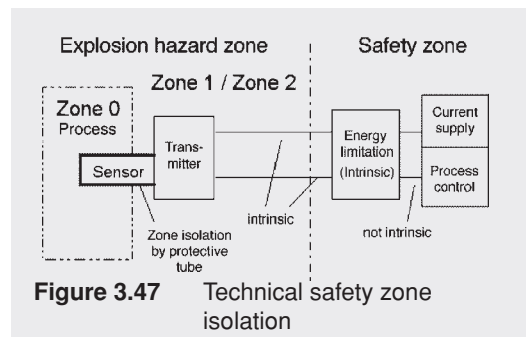
Figure 3.47   Technical safety zone isolation

Types of protection

A letter and a description of the specific concept for the equipment to prevent an explosion denote the type of ignition protection.

Isolation concept

An "intrinsic zone" is created which isolates the equipment from the explosive atmosphere around the equipment capable of being ignited so that ignition cannot occur within the "equipment intrinsic zone". Procedures, which have been developed according to this concept, are as follows.

Oil immersion - letter o

The equipment is surrounded or immersed in oil so that ignition cannot occur by sparking and arcing. This method is frequently used in power engineering, for example, for transformers and switchgears.

Pressurized enclosure or forced ventilation - letter p

The equipment is purged by fresh air or inert gas at an overpressure of approx. 8 PSI in an airtight housing. Intake of a mixture capable of exploding is prevented by positive pressure or ignition is avoided by diluting the ignitable mixture. This method is used for larger equipment and analytical rooms.

Powder filling - letter q

The equipment is filled with **explosion-retarding powder** when this method is used. It is only used in measuring technology or for special measuring instruments. On the other hand, sand filling is frequently used in the safety area as **fire protection where fuses** are concerned.

Encapsulation - letter m

The equipment is completely embedded in a gastight and permanent compound, such as epoxy. This embedding is made so that no inappropriate temperatures can occur on the surface and no ignitable atmospheres penetrate into the equipment. Encapsulation is frequently used in connection with electrical restricting measures, for example, for power supplied to a measuring instrument by battery or where variable drives are concerned.

Special mechanical (and electrical) construction concept

Where this concept is concerned, a special design ensures that an explosion in the equipment will have no effect or cannot even occur. An example of this is the Davy's miner's lamp. The following classifications come under this heading.

Increased safety - letter e

The **electrical equipment** is produced with an increased degree of mechanical and electrical safety so that no inappropriately high temperatures or electric sparking can occur as a result of cable fracture during operation. No equipment should be used under "increased safety" which, like collector motors, generate sparks themselves. Equipment with "increased safety", i.e., terminals, brushless small motors, lamps and terminal housings are frequently used in combination with "flameproof enclosures".

The ignition energy restriction concept

With this concept the **electrical energy** in explosion hazardous zones is restricted so that all potential electrical faults such as short-circuiting, wire fracture, overheating, component failure or an inadmissible surface temperature cannot occur. This method is the most frequently used concept in measurement technology because measurement technology can make do with small energies as a rule. This concept is also designated as:

Intrinsic safety - letter i

This type of protection is divided into two groups:

- in the case of intrinsic safety **ib**, if an **independent fault** with all follow-on faults is assumed for a construction element considered to be safe, ignition conditions must not occur.

- in the case of intrinsic safety **ia**, if **two independent faults** with all follow-on faults are assumed for two components considered to be safe, no ignition conditions must occur.

All electrical appliances to be used in the explosion hazardous areas Zone 0 and Zone 1 are subject to mandatory approval. A **manufacturer's certificate** is adequate for electrical equipment used in **Zone 2**.
An exception is given to mandatory approval for the use of electrical equipment in Zone 1 for intrinsic safety type of ignition protection.

The equipment is **electrically passive**, i.e. it does not generate or store electrical energy like an electric resistor or a Pt 100 thermocouple insert. The equipment must also comply with specific mechanical and electrical type specifications. The heating behavior of the equipment under power is known. In this case the equipment can be operated **without special approval**. Here again a **manufacturers certificate** is sufficient. Equipment that stores or generates electrical energy is likewise considered as intrinsically safe when all the following conditions are met:

- maximum occurring voltage is ≤ 1.2 V
- maximum flowing current is ≤ 100 mA
- maximum possible capacity is ≤ 25 mW
- maximum stored energy is ≤ 20 µJ.

Inclusion concept
This concept is similar to the isolation concept. It differs in that in addition to the electrical equipment or components being isolated from the atmosphere, explosions or fast pressure peaks that occur within the equipment or the inclusion zone will not lead to ignition through the **pressure wave**. The appropriate type of ignition protection is termed:

Explosion proof - letter d
The equipment is encapsulated tightly by embedding or by using another suitable mechanical construction to such an extent that an internal explosion does not or only slowly passes the pressure on to the environment and an **ignitable pressure surge** is prevented. This type of ignition protection was used very frequently in earlier times but is now losing popularity compared with intrinsic safety. Flameproof enclosures are used on change gears, motors, forklift trucks and pumps.

There are special cases that cannot be classified under the above-mentioned methods.

Special protection - letter s
With this type of ignition protection a unique special construction is built for a particular case of application. The acceptance conditions and regulations are determined individually for this special protection.

The standards for the respective types of ignition protection and special equipment are agreed upon throughout Europe in IEC 79-ff and EN 50014 ff. The respective regulations for the different countries, DIN VDE 0165/0170/0171 in Germany and BS 5345 in Great Britain, have been appropriately determined at state level. Details can be seen in Table 3.21.

The **CE conformity symbol** will also become mandatory for products for explosion-protected areas. The appropriate Directive 09/1994/EC of the European Parliament dated 23rd March 1994 requires that the appropriate national legislation and regulations must be agreed upon by the 31st March 1995. However, this had still not been done in Germany by February 1995. The CE conformity symbol can be applied as of 1st March 1996. It will become mandatory as of 1st July 2003. At this point in time all the technical safety approvals granted before the 1st March 1996 will become null and void, as well as all the technical safety approvals which were not granted on the basis of the CE conformity symbol by the 30th June 2003.

One example of a technical safety designation is given to conclude this section:

EEx ib IIC T5

In detail this designation means:

EEx: Approval in accordance with CENELEC

ib: Intrinsic type of **ignition protection**, suitable for use in Zone 1 and 2

IIC: Approved for all ignition mixtures (gases)

T5: Approved for all temperature classes T1 to T5 at an ambient temperature of -4°F to 105°F.

The approval agency gives its own number for the approved equipment or product. If an **X** is provided as suffix at the end of this number this means that special conditions have to be maintained for operating the equipment. These conditions are stated in the conformity certificate.

Type of ignition protection	Use in zone:	German Standard: DIN VDE 0170/0171	IEC-Standard: EN 50-	CENELEC Standard IEC: Ex ... EEx...	Code:	Examples of application
General requirements		Part 1	79-0	014		DIN EN 50
Oil immersion	2	Part 2	79-6	015	o	Transformers switchgear
Pressurized enclosure, forced ventilation	1 and 2	Part 3	79-2	016	p	Analytical rooms
Powder filling	2	Part 4	79-5	017	q	Measuring instruments
Encapsulation	1 and 2	Part 9	79-18	028	m	Measuring instruments, variable drives
Increased safety	1 and 2	Part 6	79-7	019	e	Lamps, connection boxes
Intrinsic safety	ia: 0;1;2 ib: 1;2	Part 7 Part 10	79-11	020 (equipment) 039 (systems)	i ia or ib	Measuring instruments, instrumentation variable drives
Explosion proof enclosure	1 and 2	Part 5	79-1	018	d	Motors, pumps
Special protection	1 and 2	—	—	—	s	Gas detectors

Table 3.21 Types of ignition protection in explosion protection

3.4.2 Design rules for intrinsic explosion protected measuring devices (Germany)

3.4.2.1 Electrical regulations

Minimum ignition energy

The first aim when designing intrinsically safe measuring facilities is to limit the electrical ignition energy even under faulty conditions. Here differentiation is made between the defects and ignition sources which can occur within the circuit and how much energy can get out or to the electrical interfaces. What must also be considered when combining a number of devices (in the case of measuring systems) is the combination of all the effective inductances and capacitances existing between the devices including the lines between the devices, which means line resistance, line capacitance and line inductance. Only "safe" components or "intrinsic assemblies" are approved as energy limiting components within their approved connection data. All possible faults, including voltage arcing or mechanical instability of lines, must be considered.

Safe components

The only components approved as safe components in the sense of technical safety are resistors, diodes and capacitors of a certain quality and installed under defined conditions. Even under faulty conditions they must only be loaded with two thirds of the nominal rated capacity. Transformers, which comply with the type declaration in EN 50020 and are not loaded with more than two thirds of the nominal rated capacity even in the event of a fault are also considered to be safe. Cable connections are also considered safe, provided they have a minimum cross-section, sufficient mechanical stability and are not overloaded as far as their current carrying capacity is concerned. In resistors that are loaded at more than two thirds of the nominal rated capacity but not overloaded, one failure is assessed as a **"count-**

able fault". A "countable fault" means that the failure of this component is so improbable that faults of this type only occur in rare cases. A "countable fault" can be considered separately. An "uncountable fault", on the other hand, is so probable that it must **always** be taken into account. The failure of safe diodes and capacitors under a load of up to two thirds of the rated capacity is considered as a "countable fault".

All other components are considered to be unsafe by principle. In the case of such components any number of failures has to be taken into account, i.e. uncountable faults.

Limiting components

Only **safe resistors** and **safe diodes** limit the electrical energy in **Zone 1** in conjunction with **ia**. Under certain conditions the transistor diode can be assumed to be a safe diode for **Zone 1** in connection with **ib**.

Power limitation

Fault observing philosophy

The consideration here is the maximum capacity with which the connected maximum current or maximum voltage, or the least favorable combination of the two can flow in the system through capacity adaptation. All non-safe components are theoretically circuited as worse case; this can be normal operation, short-circuiting or open circuit. For case **ib** any one safe component and for case **ia** any two safe components are then assumed to be "countable". Under these given conditions no inappropriate heating is allowed to exist in the system, or inappropriately high ignition energy in the form of current or voltage allowed to penetrate externally. Internal energy storage, which can exist through capacitances or inductances, must not give off any inappropriately high ignition energy externally. The effects of capacitances and inductances were calculated separately for the condition **ib** up to the 1st January 1994 but since the 1st January 1994 the combination effect of both

has been assessed as under condition **ia**. This can reduce the approved capacitances and inductances by a factor of ten.

Circuit power packs are a particular problem in this respect since in this case a real power transformation takes place. Here the most unfavorable case of fault is a fault by which the function of the power pack does not fail.

Where **power limitation** is concerned a distinction must be made between the following cases:

Limitation of ignitable currents is only reached under condition **ia** with "safe" ohmic resistors with a maximum capacity of two thirds of the rated capacity. Under condition **ib** two existing electronic current limitations are also possible provided all peripheral capacity conditions are kept.

Voltage limitation can only be achieved with "safe" zener diodes (z-diodes). Failure of safe z-diodes must always be assessed as a "countable" fault. This is why at least two z-diodes are always provided for valid, **failure-safe voltage limitation** in the case of **ib** and even three z-diodes in parallel as a general rule in the case of **ia**. At the same time the maximum current through the diodes should be limited by safe resistors, if necessary, so that two thirds of the maximum nominal capacity of the diodes is not exceeded.

One assembly used frequently to limit the energy is the **safety barrier**, a combination of z-diodes, resistors and a fuse.

Energy storage limitation

Capacitors are critical energy storage devices since they are frequently used in electronic circuits. They are charged to the maximum occurring voltages. Since this charging energy

$$W_C = 0.5 \cdot C \cdot U^2 \qquad (3\text{-}20)$$
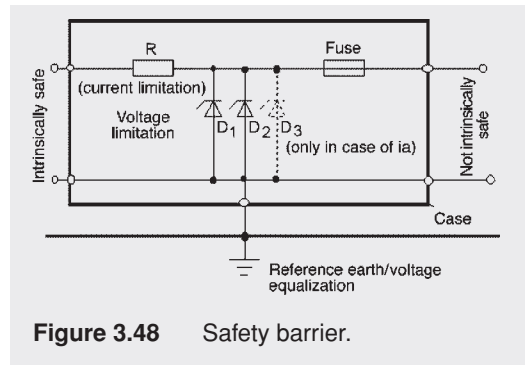
Figure 3.48   Safety barrier.

can also have an external effect as voltage or current:

a) the capacity must be kept as low as possible,
b) the maximum voltage on the capacitors must be limited by diodes and blocked externally by barrier diodes circuited in series
c) where necessary, resistors are to restrict the charging and discharging current internally and externally.

Inductances store magnetic field energy which is defined by the maximum currents occurring. This magnetic field energy

$$W_L = 0.5 \cdot L \cdot I^2 \qquad (3\text{-}21)$$

can be converted in the case of a quick breakdown of the current as a result of a line fracture or the opening of a switch to a high voltage.

The following restriction rule is applicable as a result:
a) the inductance must be kept as low as possible
b) the maximum current is to be limited by safe resistors
c) if necessary **chopping voltages** are to be limited by parallel switched diodes.

3.4.2.2 Design rules

Since the electrical energy can spread via the insulations as **creeping currents** and across gaps as flashover, a number of design rules must be observed when designing a device.

Distance conditions

The necessary structural distances must be examined individually for possible physical effects. Superimposition of all effects must be evaluated if necessary. Differentiation is made between the following distances.

Air path: this is the shortest, direct connection path between two electric conductive points isolated from each other by air. Air paths can be bridged by voltage flashover (arcing).

Creeping distance: the coupling of two electrically conductive points isolated from each other along the surface of an insulator or along the bordering surface between two materials or protective coatings. Where printed circuit boards and cases are concerned, an electric current can creep as a result of insulating surface impurities and ignitable voltage build-up.

Filament length: this is a measure that unifies the air path and creep path between two points. An imaginary filament is tightly stretched from the starting point of the energy over the surface and through the air to a possible receiver. The creep that occurs and air paths along the filament must be added up.

Fixed insulation: this is the continuity strength of a mechanically fixed insulator made of plastic or ceramic. Fixed insulators can be punctured where strong **electrical fields** are involved.

Encapsulation path: as in the case of the air path, the shortest, direct connection in non-conductive encapsulation between two electrically conductive points of the circuit. Voltage puncturing can occur with high strength electrical fields.

Safe minimum length and strength are determined for the respective forms of clearance dependent on the maximum possible voltage. These can be seen in Table 3.22.

Materials and material properties

Materials can positively influence or retard ignition depending on the surface properties. Magnesium, zinc, cadmium and aluminum increase the probability of ignition. Barium reduces the probability of ignition. As a result the quantitative limitations conforming to EN 50020 and different ignition limit curves are applicable for the materials depending upon the ignition hazard.

The mechanical design must be robust enough so that dropping and impact under the usual mechanical load can cause no inner damage. Should damage occur, damage on the inside or outside must be clearly seen from the outside to prevent further operation. Even under faulty conditions the encapsulation must not be overheated over its service temperature by components.

Insulated cases or large **insulator surfaces** can be statically charged up to 30 kV and more. Through flashover to the human body (see ESD, Section 3.3) the electrical spark can cause ignition. As a result, the surface resistance in the case of freely accessible plastic surfaces over 20 cm^2 in size must be restricted to less than 10^9 Ohm. Safe inductance of the charge to ground must also be ensured.

Nominal voltage peak values	[V]	10	30	60	90	190	375	550	750	1000	1300	1550	3300	4700	9500	15600
Creep path in air	[mm]	1.5	2	3	4	8	10	15	18	25	36	40	67	90	160	240
Creep path under protective coating	[mm]	0.5	0.7	1	1.3	2.6	3.3	5	6	8.3	12	13.3	23	30	53	80
Minimum value, creep count (IEC 112)	ia	90	90	90	90	300	300	300	300	300	300	300	see EC 587			
	ib	90	90	90	90	175	175	175	175	175	175	175				
Air path	[mm]	1.5	2	3	4	6	6	6	8	10	14	16	27	36	60	100
Encapsulation distance	[mm]	0.5	0.7	1	1.3	2	2	2	2.6	3.3	4.6	5.3	9	12	20	33
Distance by fixed isolation	[mm]	0.5	0.5	0.5	0.7	0.8	1	1.2	1.4	1.7	2.3	2.7	4.5	6	10	16.5

Table 3.22 Overview, minimum clearances in accordance with EN 50020

3.5 Chemical resistance

The chemical conversion process takes place on the surface of solid bodies when coming into contact with liquid or gaseous media. This is termed corrosion.

The risk of corrosion is particularly high on devices and construction elements which are used in corrosive media, for example acid solutions and salt solutions. Corrosion also occurs when moisture containing dissolved gases such as carbon dioxide, sulfur dioxide or hydrogen sulfide, condenses onto surfaces due to temperature changes.

Pure homogenous metal and alloys are attacked almost uniformly from the surface. Impurities and deposits on the grain borders lead to crystalline corrosion. This progressive corrosion on the grain borders is particularly dangerous because it is generally less apparent from the outside and not obvious from reduction of the weight. There are a number of ways to prevent corrosion for the most part.

1. Production and use of a metallic material in its best possible homogeneous state.

2. Alloying which improves the resistance of the material by changing its structure.

3. Surface protection using non-metallic or metallic coatings.

In the following we introduce a number of materials which play a particular role in measurement of pressure and temperature, primarily in the chemical and process industries.
Their corrosion behavior for a range of measuring media is shown in the Appendix (Section 4.2.10). This summary can only be used as a guideline. Because many factors (for example, pressure, temperature, concentration and time) contribute to corrosion no guarantee can be given for the information provided. Tests are recommended under actual working conditions where possible for special cases.

Brief description of materials:

Copper alloys = brass or bronze or low alloyed copper.

Steel = steel non-alloyed or low alloyed, respectively.

Stainless steel (316) = CrNi Mo alloy steel.

PTFE (international abbreviation for polytetrafluoroethylene (Hostalene TF, Teflon, Algoflon, Fluon, Soreflon and Polyflon are registered trademarks of various manufacturers), is almost completely resistant to all media and is only attacked by liquid sodium and fluorine compounds under high pressure).

Nickel = pure nickel > 99.2%
Corrosion resistance under reducing conditions is good and it can also be used for slightly oxidizing media because of the given passive oxide film. This protective film also ensures good resistance to caustic alkalines. Nickel is resistant to corrosion caused by stress cracking in solutions containing chloride and caustic alkaline solutions. The material can be used in the food sector.

Monel = nickel copper alloy with 30 to 40% copper
Monel materials are resistant to organic and inorganic acids, caustic alkaline solutions and salt in a wide range of working conditions. The material is best suited for reducing and oxidizing conditions; it is preferred for maritime and petrochemical applications.

Hastelloy = nickel molybdeneum iron alloys with over 55% nickel
Unlike CrNi or CrNiMo alloys the material is particularly resistant to strongly oxidizing media. It is resistant to mineral acids or organic or inorganic media contaminated with chlorine as well as formic and acetic acid. It offers resistance to moist chlorine and hypochloride.

Tantalum

This material is outstanding for its unusually high resistance to corrosion, which is comparable with that of glass and platinum. The majority of organic and inorganic materials at room temperature do not attack tantalum. This high resistance to corrosion is due to a firmly adhered surface coating that mainly consists of tantalum pentoxide. This layer dissolves at temperatures in excess of 575°F which then causes the material to become brittle.

Titanium

The good corrosion resistance of titanium is primarily due to a passive oxide coating. The material is also resistant in strongly oxidizing media even in the presence of chlorides. Titanium is only resistant to chloride when the chloride has a water content of at least 0.5%.

4 Appendix and tables

4.1 National and international standards and specifications

The following collection of standards and specifications is not claimed to be complete. It contains those standards and specifications which are useful in daily practice. The versions listed are those known to exist at the time this handbook was revised and enlarged.

4.1.1 Pressure measuring instruments with flexible measuring elements and accessories

4.1.1.1 German standards and specifications

Standards

DIN 131   Pressure, fundamental terms

DIN 6697   Bulk freight wagons with pressure discharge; pressure gauge with plate spring, radial bottom flange connection

DIN 6698   Bulk freight wagons with pressure discharge, guard and support with test connection of pressure gauge

DIN 8549   Pressure gauges with bourdon tube for devices and equipment for welding, cutting and allied processes, (case diameter 50 mm and 63 mm); replaced by DIN EN 562, edition 11/94

DIN 8896   Meteorological devices; station barometers

DIN 14421   Pressure gauges for fire-pumps

DIN 16005[1]   Pressure gauges with elastic pressure-responsive element for general use; requirements and testing

DIN 16006[1]   Pressure gauges with bourdon tube; safety requirements and testing

DIN 16007[1]   Pressure gauges with elastic pressure-responsive element for air compressors and air compressor plants; safety requirements and testing

DIN 16013[1]   Pressure gauges with capsule elements; 63 mm case diameter; accuracy classes 1.6, 2.5 and 4.0; dimensions and indicating ranges

DIN 16014[1]   -;[2] 100 and 160 mm case diameter; accuracy classes 1.0, 1.6 and 2.5; dimensions and indicating ranges

DIN 16026[1]   Pressure gauges with diaphragm element; 100 and 160 mm case diameter; diaphragm element perpendicular to plane of dial; accuracy classes 1.6 and 2.5; dimensions and indicating ranges

[1] These standards are being replaced by European Standards DIN EN 837-1 to 3.
[2] Abbreviated form. See page 351 for explanation.

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DIN 16027[1]   -;[2] 63 mm case diameter; diaphragm element parallel to plane of dial; accuracy classes 1.6, 2.5 and 4.0; dimensions and indicating ranges

DIN 16063[1]   Pressure gauges with bourdon tube; 40, 50 and 63 mm case diameter; accuracy classes 1.6, 2.5 and 4.0; dimensions and indicating ranges

DIN 16064[1]   -;[2] 80, 100, 160 and 250 mm case diameter; accuracy classes 1.0, 1.6 and 2.5; dimensions and indicating ranges

DIN 16070[1]   -;[2] 160 and 250 mm case diameter; accuracy class 0.6; dimensions and indicating ranges

DIN 16080   -;[2] 72 x 72, 96 x 96 and 144 x 144 mm case dimensions; accuracy classes 1.0, 1.6, 2.5 and 4.0; dimensions and indicating ranges

DIN 16081   Pressure gauges with capsule element; 96 x 96 and 144 x 144 mm case dimensions; accuracy classes 1.0, 1.6, 2.5 and 4.0; dimensions and indicating ranges

DIN 16085   Pressure gauges with equipment for the electrical transmission of limit signals

DIN 16086   Electrical pressure gauges, pressure transducers, pressure measuring converters, pressure gauges, terms, specifications in data sheets

DIN 16099[1]   Pointer for pressure gauges of the accuracy classes 1.0, 1.6, 2.5 and 4.0

DIN 16101[1]   Pointer adjustable for industrial pressure and temperature measuring instruments; centrally mounted pointer

DIN 16102[1]   Pointer for pressure gauges, class 0.6; 160 and 250 mm case diameter

DIN 16103[1]   -;[2] accuracy classes 0.2 and 0.3; 250 mm case diameter

DIN 16109[1]   Dials for pressure gauges, accuracy classes 1.0, 1.6, 2.5 and 4.0; single and dual graduation; scales and inscriptions

DIN 16112   -;[2] refrigerating systems; 63, 80, 100 and 160 mm case diameter; scales and inscriptions

DIN 16117[1]   Dials for pressure gauges of accuracy classes 0.2, 0.3 and 0,6; single and dual graduation; scales and inscriptions

DIN 16123[1]   Indicating ranges, spacing of scale marks and numbering of pressure gauges of accuracy classes 0.2, 0.3 and 0.6

DIN 16125   Indicating ranges, spacing of scale marks and scale points and numbering of pressure gauges in refrigerating systems

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[1] These standards are being replaced by European Standards DIN EN 837-1 to 3.
[2] Abbreviated form. See page 351 for explanation.

DIN 16128[1)]   Indicating ranges, spacing of scale marks and numbering of pressure gauges of accuracy classes 1.0, 1.6, 2.5 and 4.0

DIN 16254[1)]   Symbols and classification numbers for elastic pressure-responsive elements used in pressure gauges

DIN 16255[1)]   Pressure gauges with elastic pressure-responsive elements; designations, selection criteria, configuration, installation, operation

DIN 16257   Nominal positions and position symbols used with measuring instruments

DIN 16258[1)]   Flat sealing rings

DIN 16259   Sealing lens

DIN 16261   Stopcocks PN 16 with socket-socket connection and socket-shank connection for pressure gauges

DIN 16262   Stopcocks PN 6 and PN 16 with LH-RH union and shank connection; for pressure gauges

DIN 16263   Stopcocks PN 16 with LH-RH union and shank connection and with test connection for pressure gauges

DIN 16270   Valves PN 250 and PN 400 without test connection for pressure gauges

DIN 16271   Valves PN 250 and PN 400 with test connection for pressure gauges

DIN 16272   Valves PN 250 and PN 400 with separately lockable test connection for pressure gauges

DIN 16281   Holder for pressure gauges and fittings

DIN 16282   Siphons for pressure gauges and their accessories

DIN 16283   LH-RH union for pressure gauges and their accessories

DIN 16284   Nipple connections for pressure gauges and their accessories

DIN 16286   Screw plugs with connection shank R 1/2 form B according to DIN EN 837-1

DIN 16287   Closure and protection caps for test connections on fittings for pressure gauges

DIN 16288[1)]   Shank for connections and tapped holes for pressure gauges and pressure transducers

DIN 16310   Pressure gauges for pneumatic measuring; rectangular case; indicating; no auxiliary device

[1)] These standards are being replaced by European Standards DIN EN 837-1 to 3.

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DIN 32503	Protective caps for industrial pressure gauges for 63 mm case diameter, used in welding, cutting and allied processes
DIN 38030	Compressed air equipment for rail vehicles; pressure gauges
DIN 43790	Basic rules for the design of marked scales and pointers
DIN 50049	Types of test certificate, German version of EN 10204: 1991
DIN 75551	Pressure gauges for automobiles
DIN 75553	Pressure transmitters
DIN 75554	Pressure indicators
DIN EN 472	Pressure gauges, terms, German version EN472
DIN EN 562	Pressure gauges for welding, cutting and allied processes
DIN EN 837-1	Draft: Pressure gauges Part 1: pressure gauges with bourdon tube, dimensions, measuring, requirements and testing, German version prEN 837-1: 1992
DIN EN 837-2	Draft: Pressure gauges Part 2: Selection and installation recommendations for pressure gauges, German version prEN 837-2: 1994
DIN EN 837-3	Draft: Pressure gauges Part 3: Pressure gauges with diaphragm and capsule, dimensions, measuring, requirements and testing; German version prEN 837-3: 1994
DIN VDE 0470 Part 1	Types of protection using a case (IP code) (IEC 529 (1989), 2nd edition) German version EN 60529: 1991

PTB test regulations

PTB Vol. 15   Liquid pressure gauges

Steel test specifications

SEB 386470   Hydraulics and pneumatics; pressure gauges with bourdon tube and glycerine-water filling; selection for hydraulic systems

VDI guidelines

VDE/VDI 3512 Sheet 3: Measuring arrangements for pressure measurements

VdTÜV codes of practice

VdTÜV Pressure 100/1   Requirements to be met by pressure monitors and pressure limiters for steam boilers

VG standards

VG 85990   Industrial pressure gauges, antimagnetic

VG 85992   Industrial pressure gauges; round, antimagnetic

VG 85993   Industrial pressure gauges; rectangular, antimagnetic

Calibration regulations (EO)

EO Annex 15-4 = PTB-A15.4 non-invasive blood pressure measuring instruments

EO Annex 16   = PTB-A16 Pressure gauges

EO Annex 18-8 Tyre pressure gauges (now EC Guideline 86/217)

DKD guidelines

DKD-R-3-2   Guideline of the German Calibration Service: Guideline for the calibration of pressure gauges within the framework of the German calibration service (DKD)

DKD-R-3-3   Guideline of the German Calibration Service: Guideline for the calibration of force gauges within the framework of the German calibration service (DKD)

DKD-R-3-4   Guideline of the German Calibration Service: Guideline for the calibration of piston pressure gauges within the framework of the German calibration service (DKD)

Technical regulations for drink dispensing systems

TRSK 301   Requirements to be met by pressure reducers, intermediate pressure controllers and wall bridges

TRSK 304   Requirements to be met by pressure gauges

Accident prevention regulations

VBG 15   Welding, cutting and allied processes, reference: 89/392/EEC, 89/655/EEC

VBG 16   Compressors

VBG 20   Refrigerating plants, heat pumps and cooling equipment, reference: 80/655/EEC, 91/392/EEC

VBG 61   Gases, reference: MEDGV

VBG 62   Oxygen, reference: 89/392/EEC, 89/655/EEC

Guidelines for the official testing of pesticides, Part VII

1-1.1.1 or   Characteristics of spraying equipment for field crops
1-1.1.2 or   for indoor crops, Section 13.2, Pressure indicators

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1-1.1.3 or   Characteristics of portable, non-powered spraying equipment,
1-1.1.4 or   portable, powered spraying equipment, Section 13.2 Pressure indicators

4.1.1.2 International standards and specifications

ISO standards

ISO 5171   Pressure gauges used in welding, cutting and allied processes

International recommendations concerning measuring

OIML R 16   Pressure indicators on blood pressure measuring instruments

OIML R 17   Pressure gauges - vacuum meters - pressure and vacuum gauges with direct indication

OIML R 19   Pressure gauges - vacuum meters - pressure and vacuum gauges; recording instruments

OIML R 53   Measuring characteristics of elastic pressure-responsive elements for use in pressure measurement. Methods of their determination

OIML R 101   Indicating and recording pressure gauges - vacuum meters - pressure and vacuum gauges (industrial measuring instruments)

OIML R 109   Pressure gauges - vacuum meters (precision measuring instruments)

OIML R 110   Pressure balances

Guidelines of the European Community

86/217/EEC
Guideline of the Council dated 26th May 1986 for harmonization of the legal regulations of the member countries for air pressure gauges.

EECR 594/91
Regulation (EEC) No. 594/91 of the Council dated 4th March 1991 concerning substances which result in depletion of the ozone layer.

EECR 3952/92
Regulation of the Council dated 30th December 1992 for amendment of Regulation (EEC) No. 594/91 concerning the accelerated abandonment of substances which result in depletion of the ozone layer.

4.1.1.3 Non-German standards and specifications

Australia

AS 1349   Bourdon tube pressure and vacuum gauges

Belgium

NBN 363 H   Pressure gauges, general conditions

Taiwan

CNS D 2039   Oil pressure gauges for automobiles

CNS E 3007   Pressure gauges with bourdon tube for railway equipment

China

GB 1226   Pressure gauges with bourdon tube, class 1.0 to 4.0

GB 1227   Precision pressure gauges with bourdon tube, class 0.25 and 0.4

GB 11152   Pressure gauges with remote transmitters

France

NF A84-410   Gas welding equipment, pressure gauges for welding,
NF EN 562   cutting and allied processes, requirements and tests

NF A84-430   Equipment for oxy-acetylene welding, pressure reducers for gas cylinders for compressed gases and acetylene, for welding, cutting and allied processes, requirements and testing

NF E15-012   Pressure gauges, case made of metal - connection socket

NF E15-013   Pressure gauges with elastic pressure-responsive element, dials

NF E15-024   Pressure gauges, fixture for test pressure gauges (regulation for land applications)

NF E15-025   Pressure gauges with elastic pressure-responsive element, indicating range from 2.5 mbar to 250 mbar

NF E15-026   Pressure gauges with elastic pressure-responsive element, indicating range from 0.4 to 1600 mbar

NF E15-027   Pressure gauges with elastic pressure-responsive element, acceptance test

NF E15-028   Pressure gauges, terms (European Standard EN 472)
NF EN 472

NF E15-030   Accessories for pressure gauges, connection sockets

NF E15-031   Pressure gauges, recording pressure gauges made of metal

NF E15-033   Pressure gauges, pressure gauges with elastic pressure-responsive element and with damping liquid

NF E15-034   Pressure gauges with elastic pressure-responsive element, differential pressure gauges

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NF E15-035	Pressure gauges with elastic pressure-responsive element, measuring instruments of classes 0.1, 0.25 or 0.5
NF E15-038	Pressure gauges with elastic pressure-responsive element, absolute pressure gauges
NF E15-100	Pressure gauges and thermometers with elastic pressure-responsive element with equipment for transmitting limit signals
NF E29-382	Fittings, blow-out and pressure measuring nipples
NF L72-310	Aviation instruments, on-board pressure gauge with round scale
NF M 88-901	Oil industry, test instruments. Bourdon pressure gauges
NF R14-210	Road vehicles, round instruments, mounting diameter and scale graduation
NF R 63-302	Road vehicles, workshop equipment, instrument for checking tyre pressure
NF S76-036 NF EN 145	Respiratory equipment, regeneration equipment with pressurized oxygen, oxygen safety equipment, requirements, testing, identification
NF U26-132	Pesticides, spraying and spraying equipment, connection dimensions for nozzles and pressure gauges
NF X 10-500	Vacuum systems - Nomenclature and definitions - basic terms
NF X 10-520	Vacuum systems - Pressure measurement in industrial vacuum plants
NF C 10-521	Vacuum systems, vacuum meters, calibration, direct comparison methods
NF X 10-523	Vacuum systems, general calibration methods for low-pressure gauges
NF X 10-524	Vacuum systems, vacuum meters, calibration, dynamic method

Great Britain

BS 759 P.1	Valves, gauges and other safety fittings for application to boilers and to piping installations for and in connection with boilers, valves, brackets and equipment components
BS 1042 P.1 Section 1.5	Flow measurement of liquids in closed lines, differential pressure gauges, guide to deviations from the conditions laid down in Section 1.1
BS 1123 P.1	Safety valves, indicating instruments and melting plugs for compressed air and inert gas systems, installation guide
BS 1780	Bourdon tube pressure gauges and vacuum gauges

BS 2520	Units, terms of reference and correction tables for barometers; application
BS 3127	Specification for bourdon tubes made of steel and nonferrous metal
BS 4613 P.1	Tyre pressure gauges, specification, portable type with indicating bar
BS 4613 P.2	Tyre pressure gauges, specification, portable type with dial
BS 4613 P.3	Tyre pressure gauges, specification, tyre pressure gauges for road vehicles
BS 6174	Specification for differential pressure transmitters with electrical outputs
BS 6356 P.2	Spraying apparatus for plant protection, connection dimensions for nozzles and pressure gauges
BS 6739	Guide to measuring instruments in process control systems, equipment arrangement
BS 6752	Pressure gauges with bourdon tube for welding, cutting and allied processes
BS EN 250	Breathing equipment, autonomous light diving equipment with compressed air, requirements, testing, identification

Israel

S I 697-68	Pressure gauges, technical terms

Italy

UNI 4657	Pressure gauges, vacuum gauges, pressure/vacuum gauges, overview, replacement for UNI 8357
UNI 4663	-,-,[2] scale division and numbering
UNI 4664	-,-,[2] pointers
UNI 4665	-,-,[2] union nuts and connectors
UNI 4666	-,-,[2] stopcock with connection R 1/4A, PN 10
UNI 4667	-,-,[2] stopcock with connection R 1/2A, PN 16
UNI 4668	-,-,[2] stopcock with connection R 1/2A and connection for checking instrument PN 16
UNI 4669	-,-,[2] valve with connection R 1/2A for pressure gauges, PN 100
UNI 4670	-,-,[2] valve with connection R 1/2A and connection for checking instrument PN 1000
UNI 4672	-,-,[2] syphons (U-shaped, circular) with adaptor

[2] Abbreviated form. See page 351 for explanation.

UNI 4673	-,-,[2] locking adaptors with identical or different threads
UNI 4674	-,-,[2] soldered connections
UNI 4675	-,-,[2] connectors for leading through panels
UNI 4676	-,-,[2] connectors
UNI 4677	-,-,[2] shank connectors and nuts
UNI 8049	-,-,[2] measuring ranges for pressure and conversion of pressure units
UNI 8291	-,-,[2] mounting position and relational graphic illustrations
UNI 8292	-,-,[2] nominal widths, dimensions and types of mounting
UNI 8293	-,-,[2] accuracy classes and error limits in numerical values
UNI 8294	-,-,[2] symbols of elastic pressure-responsive elements
UNI 8295	-,-,[2] scales and inscriptions for single graduation
UNI 8537	-,-,[2] with resilient element - type and case size allocated to accuracy classes
UNI 8538	-,-,[2] design characteristics with elastic pressure-responsive elements
UNI 8539	-,-,[2] with elastic pressure-responsive elements and design characteristics, stainless steel execution
UNI 8540	-,-,[2] additional characteristics for liquid-filled instruments, including stainless steel execution
UNI 8541	-,-,[2] with safety requirements, including stainless steel execution
UNI 8633	-,-,[2] technical regulations for testing and delivery
UNI 8896	-,-,[2] case protection types and tests
UNI 8987	-,-,[2] terms and concepts
UNI 8988	-,-,[2] for oxygen and acetylene pressure cylinders, design characteristics

India

| IS 3624 | Pressure and vacuum gauges |

Japan

| JIS B 7505 | Pressure gauges with bourdon tube |
| JIS B 7546 | Pressure gauges with diaphragm |

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[2] Abbreviated form. See page 351 for explanation.

JIS D 5603   Oil pressure gauges for automobiles

JIS E 4118   Pressure gauges with bourdon tube for railway equipment

Canada

CSA CAN/CSA - Z 305 - M87
                     Pressure controllers, pressure gauges and flow meters for medical gases

Netherlands

NEN 927   Pressure gauges, general terms

NEN-EN 472   Pressure gauges, terms

NEN-EN 562   Pressure gauges for welding, cutting and allied processes

NEN-EN 837-1   Draft: Pressure gauges; Part 1: Pressure gauges with bourdon tubes, dimensions, measuring, requirements and testing

Norway

NS 5500   Pressure gauges, nomenclatures, dimensions and scales

NS 5503   Safety pressure gauges, dimensions and scales

NS 5504   Calibration of pressure sensors, definitions of terms, accuracy, certification for test standards, methods, test record for indicating accuracy

Austria

The acting standards committee has withdrawn the Austrian standards. Contracting parties base their agreements on the standards of other countries, in particular DIN standards as listed in Section 4.1.1.1.

Portugal

The majority of products are manufactured and delivered in accordance with DIN standards.

Switzerland

DIN standards are adopted and applied directly in most cases.

Spain

It is customary to apply ANSI and DIN standards for pressure gauges.

Saudi Arabia

SSA 176   Calibration methods for bourdon tube pressure and vacuum gauges

SSA 177   Bourdon tube pressure and vacuum gauges

South Africa

SABS 1062   Specification for pressure and vacuum gauges

Sweden

SMS 1554   Pressure gauges, technical requirements

SMS 1555   Pressure gauges, round scales, indicating ranges, spacing of scale marks and numbering

SMS 1556   Pressure gauges, scale design, inscriptions

SMS 1557   Pressure gauges with bourdon tube and central scale

SMS 1560   Pressure gauges, pointers

SMS 1562   Pressure gauges, terms

Russia

GOST 5.1120 Weight-loaded piston pressure gauge MP-600

GOST 1701   Pressure gauges and mechanical pressure indicating instruments for automobiles

GOST 2405   Indicating pressure gauges, vacuum gauges and pressure/vacuum gauges

GOST 6521   Spring-loaded standard pressure gauges and vacuum gauges

GOST 7919   Recording pressure, vacuum and pressure/vacuum gauges

GOST 8625   Indicating pressure gauges, vacuum gauges and pressure/vacuum gauges

GOST 9921   Tyre pressure gauges, manual

GOST 9933   U-tube absolute pressure gauges and pressure/vacuum gauges

GOST 13717   Indicating electrical contact instruments applying the manometric principle

GOST 14010   Pressure and differential pressure transmitters

GOST 15907   Borehole pressure gauges

GOST 18140   Differential pressure gauges

GOST 22520   Pressure, vacuum and differential pressure transmitters with analogue electrical output signals

GOST 22725   Standard pressure gauges with manganin resistor for high pressures

GOST 24446   Standard deformation pressure gauges and vacuum gauges with defined scale

U.S.A.

ANSI/
ASHRAE 41.3   Methods of taking pressure measurements

ANSI/
ASME 40.1   Pressure gauges, indicating dial type - Elastic element

ANSI/
ASME PTC 19.2   Pressure measuring instruments and apparatus, Part 2

API RP 550 P.1   Section 4 - Pressure, process and control instruments for pressure for refinery applications

UL 252A   Pressure gauges for compressed air service - Low pressure

UL 299   Dry chemical fire extinguishing agents (Section 44 - Pressure gauges)

UL 393   Indicating pressure gauges for fire fighting

UL 404   Pressure gauges for compressed air service - High pressure

NBS Monograph 65   Acceptance data for piston pressure gauges

ANSI/ISA S37.3   Strain foil gauges for pressure measuring

ANSI/ISA S37.6   Potentiometric remote pressure transmitters

4.1.2 Flanges, connections and fittings

The following standards and specifications concerning flanges and fittings are used in connection with pressure and flow measurement:

4.1.2.1 German standards and specifications

Standards

DIN 2353   Solderless pipe couplings with cutting ring, complete coupling with overview

4 Appendix and tables

DIN 2500 Flanges; general statements, survey

DIN 2501 Part 1 Flanges; mating dimensions

DIN V 2505 Calculation of flanged joints

DIN 2512 Flanges; tongue and groove, nominal pressures 10 to 160, design dimensions, rings

DIN 2513 -;[2] projection and recess, nominal pressures 10 to 100, design dimensions

DIN 2514 -;[2] groove for rubber seal ring, nominal pressures 10 to 40, design dimensions

DIN 2519 Steel flanges, technical terms of delivery

DIN 2526 Flanges; types of contact faces

DIN 3158 Refrigerant fittings; safety specifications; testing, identification marks

DIN 3159 Flanged joints for refrigerant fittings up to ND 25

DIN 3202 Part 1 Face-to-face dimensions of valves; flanged valves

DIN 3202 Part 2 Face-to-face dimensions of valves; weld-on valves

DIN 3202 Part 3 Face-to-face dimensions of valves; wafer type valves

DIN 3202 Part 4 Face-to-face dimensions of valves; valves with screwed sockets

DIN 3202 Part 5 Face-to-face dimensions of valves; valves with connection by compression fittings

DIN 3211 Part 1 Valves; nomenclature and definitions

DIN 3230 Part 1 Technical conditions of delivery for valves; enquiry, order and delivery

DIN 3230 Part 2 -;[2] general requirements

DIN 3230 Part 3 -;[2] survey of possible test methods

DIN 3230 Part 4 -;[2] valves for water supply service, requirements and tests

DIN 3230 Part 5 -;[2] valves for gas installations and gas pipelines, requirements and tests

DIN 3230 Part 6 -;[2] valves for combustible fluids, requirements and tests

DIN 3239 Part 1 Weld-on ends of valves for butt-welding

DIN 3239 Part 2 Weld-on ends of valves for socket welding

[2] Abbreviated form. See page 351 for explanation.

DIN 3840   Bodies of valves; calculation of internal pressure strength

DIN 3852 Part 1   Screwed plugs, tapped holes, with metric fine pitch thread; general outlay of types

DIN 3852 Part 2   -,-,-;[2)] with Whitworth pipe pitch thread; general outlay of types

DIN 3852 Part 3   -,-,-;[2)] with metric fine pitch thread, form F and form W; general outlay of types

DIN 3852 Part11   -,-,-;[2)] screwed plugs form E; general outlay of types

DIN 8546   Pressure reducers for gas cylinders used for welding, cutting and allied processes; terms, requirements and testing. Replaced by DIN EN 585

DIN 8960   Refrigerants; requirements

DIN 8962   Refrigerant codes

DIN 8975 Part 1   Refrigeration plants; safety principles for construction, equipment and erection; design

DIN 11850   Stainless steel tubes for the food industry; dimensions, materials

DIN 11851   Food industry fittings; stainless steel screwed pipe connection, threaded couplings, conical couplings, coupling nuts, gaskets

DIN 11852   -;[2)] shapes, T-pieces, bends

DIN 11854   -;[2)] stainless steel hose unions, threaded hose couplings, conical hose couplings

DIN 11861   Fittings for the beverage and dairy industry, rubber sealing rings, requirements, testing

DIN 11887   Food industry fittings, round thread connections; threaded couplings, conical couplings

DIN 32509   Hand-operated shut-off valves for welding, cutting and allied processes; types safety requirements, testing

DIN EN 19   Identification of industrial fittings for general use

DIN EN 585   Gas welding equipment - pressure reducers for gas cylinders used for welding, cutting and allied processes up to 200 bar; German version of EN 585

[2)] Abbreviated form. See page 351 for explanation.

4 Appendix and tables

AD codes of practice

AD B 0   Calculation of pressure vessels

AD B 8   Flanges

AD B 9   Cut-outs in cylinders, cones and spheres

AD B 10   Thick-walled cylindrical shells under internal pressure

AD W 2   Austenitic steels

AD W 9   Flanges made of steel

AD W 10   Materials for low temperatures, ferrous materials

Technical regulations for high-pressure gas lines

TRGL 133   Flanges, seals, screws and nuts; materials, production, testing

Technical regulations for tanks

TRT 024   Technical guidelines for tanks; identical safety for components (fittings)

VDMA standards

VDMA 24421   Fittings; acceptance and testing of fittings; definitions, extent, cost

VdTÜV codes of practice

VDTÜV MB 1055   Guidelines for machining the ends of tubes, formed parts and fittings for pipelines

VdTÜV MB 1065   Guidelines for the testing of fittings for gases and hazardous liquids

VdTÜV resolutions

VdTÜV Wei 25   TÜV Nuclear Technology Office of VdTÜV; resolution 25

VG standards

VG 85002   Identification of pipeline fittings

VG-85003-2   Fittings; technical specifications; compendium of possible requirements and tests

Technical regulations for acetylene plants (TRAC)

TRAC 204   Acetylene pipelines

Technical regulations for compressed gases

TRG 101   Compressed gases; gases

TRG 102   Compressed gases; gas mixtures

TRG 103   Compressed gases; liquid, deep-cooled compressed gases

TRG 104   Compressed gases; optional use of gas cylinders

4.1.2.2 Non-German standards

France

NF A84-430   Equipment for oxy-acetylene welding, pressure reducers for gas cylinders, for compressed gases and acetylene, for welding, cutting and allied processes, requirements and tests

NF E29-002   Pipelines - pressures and temperatures, concepts

NF E29-203   -,[2] unalloyed, alloyed, stainless austenitic steel flanges and collars

NF E29-204   -,[2] flanges and collars made of forged steel, materials, mechanical properties, production, testing

NF E20-206   -,[2] flanges made of unalloyed cast iron, definitions, dimensions, requirements

NF E29-207   -,[2] flanges made of copper or copper alloys, definitions, dimensions, requirements

NF E29-209   Pipelines, unalloyed, alloyed, stainless austenitic steel flanges and collars, requirements

NF E29-210   Pipelines, orifice flanges for throttles

NF M87-500   Mineral oil industry, flanges, general specifications

NF M87-501   Mineral oil industry, flange sealing faces

Great Britain

BS 10   Flanges and bolts for pipes, valves and connectors, specifications

BS 1560 P.3   Round flanges for tubes, valves and fittings,
Sect.3.1   flanges made of steel, cast iron and copper alloys, steel flanges

[2] Abbreviated form. See page 351 for explanation.

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BS 1560
Sect.3.2   -,-,-,[2] cast iron flanges

BS 1560
Sect.3.3   -,-,[2] made of copper alloys and composite materials

BS 4504 P.3   Round flanges for pipes, valves and fittings
Sect.3.1   (according to nominal pressure ratings), flanges made of steel, cast iron and
                  copper alloys, flanges made of copper alloys and composites

BS 4504
Sect.3.2:1989 -,-,-,[2] cast iron flanges

BS 4504
Sect.3.3:1989 -,-,[2] made of copper alloys and composite materials

Israel

S.I.   60   Pipe flanges
              60.1   - General
              60.2   - Joint dimensions
              60.3   - Sealing faces
              60.4   - Ring flanges
              60.5   - Slip-fit flanges
              60.6   - Flanges with welding nipple
              60.7   - Threaded flange
              60.8   - Blind flange

Italy

UNI 2223   Metal flanges for pipelines, hole configuration and round flange, mating
              dimensions

UNI 2224   -,-,[2] oval flanges, mating dimensions

UNI 2225   -,-,[2] surface, tightness, single slot

UNI 2226   -,-,[2] double slot (tongue-and-groove geometry)

UNI 2227   -,-,[2] dimensions of tongue-and-groove geometry for round seals. PN 10 to 40

UNI 2229   -,-,[2] step, surface, tightness

UNI 2231   Common flanges for pipelines, recalculation of fixed flanges

UNI 2232   -,[2] recalculation of free flanges

[2] Abbreviated form. See page 351 for explanation.

UNI 2233	-,[2] list of types
UNI 6078	-,[2] conical surface, sealing face for lens seal, PN from 64 to 250
UNI 6100	-,[2] tolerances and identification
UNI 2234 to 2239	-,[2] grey cast iron, PN from 2.5 to 40
UNI 2240 to 2240	-,[2] grey cast iron, PN from 16 to 100
UNI 6079 and 6080	-,-,[2] PN 160 and PN 250
UNI 2245	-,[2] cut, PN 2.5; DN from 2 1/2 to 4, and PN 6, DN from 3/8 to 2
UNI 2246 to 2248	-,-,[2] PN 6; PN 16; PN 40
UNI 2249 and 2250	-,-,[2] reduced circular PN 1 and PN 2.5
UNI 2251 and 2252	-,-,[2] oval collar ring PN 6 and PN 16
UNI 2253 to 2257	-,-,[2] circular collar ring PN 6 to PN 100
UNI 2275	Metal flanges for pipelines, lap welded flanges oval, PN 2.5, DN from 65 to 100; PN 6, DN from 10 to 50
UNI 2276 to 2278	-,-,-,[2] but circular - PN 6; PN 10; PN 16
UNI 6081	-,-,-,[2] oval - PN 16
UNI 6082 to 6084	-,-,-,[2] circular - PN 2.5; PN 25; PN 40
UNI 6091 to 6099	Metal flanges for pipelines, blind flanges, PN 6 to PN 250
UNI 2279 to 2286	Metal flanges for pipelines, but welded flanges, PN 2.5 to PN 100
UNI 6085 and 6086	-,-,[2] PN 160 and PN 250

[2] Abbreviated form. See page 351 for explanation.

UNI 4334	Ring seals for single-recess flanges
UNI 2287 to 2293	Metal flanges for pipelines, butt welded flanges with bearing collar ring, PN 1 to PN 40
UNI 2299 and 2300	Metal flanges for pipelines, lap welded flanges with bearing ring, PN 25 and PN 40
UNI 6087 to 6090	-,-,[2] and for pipes with bearing edge PN 2.5 to PN 16

Japan

JIS B 2201	Pressure calculation for ferrous materials in pipe flanges
JIS B 220	Weld-on steel pipe flanges

Sweden

SS 3351	Pipe couplings, threaded couplings for the food industry
SS 3353	Pipe couplings, hexagonal and slotted union nuts for the food industry

U.S.A.

ANSI B 16.1	Cast iron pipe flanges and cast iron flange fittings
ANSI B 16.5	Pipe flanges and pipe fittings
ANSI B 16.11	Forged steel fittings with welding or threaded neck
ANSI B 16.34	Valves with flange or weld-on end

Russia

GOST 12820	Flat weld-on flanges made of steel for NP 0.1 - 2.5 MPa
GOST 12821	Butt weld-on flanges made of steel for NP 0.1 - 20.0 MPa
GOST 9112	Pipe couplings with double conical ring
GOST 9399	Threaded flanges made of steel for NP 20 - 100 MPa
GOST 9400	Threaded joint ends for fittings, connectors and pipelines with lens seals for NP 20 - 100 MPa
GOST 12678	Pressure controllers based on the direct mode of operation
GOST 12815	Flanges for fittings, connectors and pipelines for NP 0.1 to 20 MPa

[2] Abbreviated form. See page 351 for explanation.

4.1.3 Electrical measuring instruments and pressure gauges

4.1.3.1 German standards and specifications

Standards

DIN 16086   Electrical pressure gauges, pressure transducers, pressure measuring converters, pressure gauges, concepts, specifications in data sheets

DIN 16230   Measurement and control; charts for strip chart recorders

DIN 43701 Part 1   Electrical switchboard instruments; technical terms of delivery, general conditions

DIN 43701 Part 2   Electrical switchboard instruments; technical terms of delivery, indicating ammeters, voltmeters and power meters

DIN 43701 Part 3   Electrical switchboard instruments; technical terms of delivery; measuring instruments for electric thermometers

DIN 43701 Part 4   Electrical switchboard instruments; technical terms of delivery, indicating measuring instruments for transducers

DIN 43750   Electronic measuring equipment; documentation to be supplied (= IEC 278-1968)

DIN 43751 Part 1   Measurement and control; digital measuring instruments; general statements concerning concepts, tests and data sheet specifications (= IEC 66(Sec)49-1985)

DIN 43751 Part 2   -; -;[2] measuring instruments for the measurement of analogue values; concepts, tests and data sheet specifications (= IEC 66(Sec)50-1985)

DIN 43751 Part 3   -; -;[2] measuring instruments for the measurement of digital values; concepts, tests and data sheet specifications (= IEC 66(Sec)51-1985)

DIN 43751 Part 4   -; -;[2] measuring instruments for the measurement of time-related values; concepts, tests and data sheet specifications (= IEC 66(Sec)50-1985)

DIN 43781 Part 1   Measurement and control; electrical measuring instruments; direct acting recording instruments and their electrical accessories (= IEC 258-1968)

DIN 43781 Part 2   Measurement and control; electrical measuring instruments; direct acting recording instruments and their electronic accessories (= IEC 258-1968)

DIN 45140 Part 1   Measurement and control; connection codes for measurement and control instruments; specification as an alphanumeric system

DIN 45140 Part 2   -; -;[2] specification as a translation key

DIN 45140 Part 3   -; -;[2] specification for process management systems

[2] Abbreviated form. See page 351 for explanation.

4 Appendix and tables

DIN 45141	Measurement and control; threaded joints for air tubes of measuring and control instruments
DIN 45670	Shaft vibration measuring equipment; requirements to be met by a measuring device for monitoring relative shaft vibrations
DIN IEC 359	Specification concerning the operating characteristics of electrical and electronic measuring instruments; identical with IEC 359: 1987
DIN IEC 468	Processes for measuring the specific (electrical) resistance of metallic materials
DIN EN 60688	Measuring transducers for converting alternating current values into analogue and digital signals (IEC 688: 1992)
DIN IEC 625 Part 1:	A byte-serial and bit-parallel interface system for programmable measuring instruments; Functional, electrical and mechanical stipulations, applications of the system and guidelines for the development engineer and user
DIN IEC 625 Part 2:	A byte-serial bit-parallel interface system for programmable measuring instruments; Agreement concerning codes and data formats
DIN IEC 770	Methods of assessing the operating characteristics of measuring transducers for control functions in industrial process engineering systems
DIN IEC 770 Part 2:	Measuring transducers for control functions in industrial process engineering systems; Instructions for the acceptance and operating inspection; identical with IEC 770-2: 1989

PTB test regulations

PTB Volume 12	Measuring converters
PTB Volume 17	Immunity to interference; processes for testing the effect of electromagnetic interference on measuring instruments

PTB technical guidelines

PTB E	Measuring instruments for electricity, summary of contents
PTB E1	-,[2] inspection of officially approved test centres
PTB E21	-,[2] electronic voltage, standards for use in the legal weights and measures system

[2] Abbreviated form. See page 351 for explanation.

KTA safety regulations

KTA 3505   Type testing of measurement transmitters and measuring transducers used in the reactor security system

Technical regulations for combustible liquids

TRbF 511   Guideline for the production of limit value transmitters

4.1.4 Thermometers, temperature gauges and accessories

4.1.4.1 German standards and specifications

Standards

DIN 1341   Heat transfer; definitions, characteristic parameters

DIN 12769   Liquid-in-glass thermometers; survey

DIN 12770   Laboratory glassware; liquid-in-glass thermometers; general requirements

DIN 12771   Laboratory glassware; enclosed scale calorimeter thermometers, measuring range 6°C

DIN 12775   Laboratory glassware; laboratory thermometers, scale values 0.1°C, 0.2°C and 0.5°C

DIN 12778   Laboratory glassware; laboratory thermometers, scale values 1°C and 2°C

DIN 12779   Laboratory glassware; laboratory thermometers, with high-speed indication (distillation thermometers)

DIN 12781   Laboratory glassware; laboratory straight enclosed scale thermometers

DIN 12784   Laboratory glassware; thermometers with ground joint

DIN 12785   Laboratory glassware; special-purpose laboratory thermometers

DIN 12786   Laboratory glassware; enclosed-scale thermometers for thermo-economic measurements

DIN 12787   Mineral oil and fuel testing; thermometer nipples

DIN 12789   Laboratory glassware; Beckmann thermometers, adjustable-range enclosed-scale thermometers

DIN 12799   Laboratory glassware; solid stem general purpose thermometers

DIN 12878	Laboratory electrical appliances; adjustable liquid-in-glass contact thermometers and relays, general and safety requirements and testing, reference: GSG
DIN 13100	Medical mercury-in-glass thermometers; clinical thermometers, veterinary thermometers (enclosed-scale thermometers), principal dimensions, requirements
DIN 16160	Thermometers; concepts
DIN 16167	Glass thermometers for industrial purposes with round case; nominal size 160, straight type, dimensions and indicating ranges
DIN 16168	-;[2] nominal size 160, 90° angle type, dimensions and indicating ranges
DIN 16174	-;[2] nominal size 250, straight type, dimensions and indicating ranges
DIN 16175	-;[2] nominal size 250, 90° angle type, dimensions and indicating ranges
DIN 16176	-;[2] nominal size 250, 135° angle type, dimensions and indicating ranges
DIN 16179	Screwed-in ends and protecting tubes for glass thermometers for industrial processes
DIN 16181	Glass thermometers for industrial purposes with V-shape case; nominal size 110, straight type, dimensions and indicating ranges
DIN 16182	-;[2] nominal size 110, 90° angle type, dimensions and indicating ranges
DIN 16185	-;[2] nominal size 150, straight type, dimensions and indicating ranges
DIN 16186	-;[2] nominal size 150, 90° angle type, dimensions and indicating ranges
DIN 16189	-;[2] nominal size 200, straight type, dimensions and indicating ranges
DIN 16190	-;[2] nominal size 200, 90° angle type, dimensions and indicating ranges
DIN 16191	-;[2] nominal size 200, 135° angle type, dimensions and indicating ranges
DIN 16194	Spacing of scale marks and numbering for glass thermometers for industrial purposes, V-shape, nominal size 110, 150 and 200
DIN 16195	Glass thermometers for industrial purposes with round or V-shaped case; requirements and testing
DIN 16203	Pointer thermometers; spring and bimetal thermometers; requirements and testing
DIN 16204	Pointer thermometers; bimetal thermometers; accuracy classes 1 and 2; nominal case diameters 63, 80, 100 and 160 mm; dimensions and indicating ranges

[2] Abbreviated form. See page 351 for explanation.

DIN 16205	Pointer thermometers; spring thermometers with an elastic element; accuracy classes 1 and 2; nominal case diameters 63, 80, 100 and 160 mm; dimensions and indicating ranges
DIN 16206	Pointer thermometers; spring thermometers with remote control; accuracy classes 1 and 2; nominal case diameters 60, 63, 80, 100 and 160 mm; nominal case sizes 72 x 72, 96 x 96 and 144 x 144; dimensions and indicating ranges
DIN 43700	Measurement and control; measurement and control instruments for panel mounting, nominal dimensions and through-hole dimensions
DIN 43790	Basic rules for the design of marked scales and pointers
DIN 50049	Metal products, types of test certificate, German version EN 10204: 1991
DIN 58653	Meteorological instruments; minimum thermometers
DIN 58654	Meteorological instruments; maximum thermometers
DIN 58655	Meteorological instruments; ground thermometers 20 to 310 mm
DIN 58656	Meteorological instruments; thermometer hut
DIN 58658 P. 1	Drums and movements for recording instruments; removable drums, movements
DIN 58658 P. 2	-;[2] drums connected with clock movements
DIN 75575	Remote thermometers for automobiles
DIN VDE 0470 Part 1	Types of case protection (IP code) (IEC 529 (1989), 2nd edition) German version EN 60529: 1991

Calibration regulations for temperature gauges

EO 14-1	Liquid-in-glass thermometers
EO 14-2	Thermoelements
EO 14-3	Pointer thermometers
EO 14-4	Portable electrical thermometers
EO 14-5	Refrigerator thermometers
EO 15-1	Medical thermometers

PTB requirements (PTB-A)

PTB-A 14.1	Liquid-in-glass thermometers
PTB-A 14.2	Thermoelements
PTB-A 14.3	Pointer thermometers
PTB-A 14.5	Refrigerator thermometers
PTB-A 15.1	Medical electric thermometers

[2] Abbreviated form. See page 351 for explanation.

4 Appendix and tables

Federal German statutory and administrative regulations

General administrative regulation for the calibration of measuring instruments; testing of liquid-in-glass thermometers

4.1.4.2 International standards and specifications

International standards

ISO 386   Liquid-in-glass laboratory thermometers; principles for execution, design and use

ISO 653   Long precision solid-stem thermometers

ISO 654   Short precision solid-stem thermometers

ISO 655   Long precision thermometers with enclosed scale

ISO 656   Short precision thermometers with enclosed scale

ISO 1770   Solid stem thermometers for general purposes

ISO 1771   Thermometers with enclosed scale for general purposes

ISO 4786   Adjustable thermometers of enclosed-scale type

ISO 6152   Thermometers for use with alcohol (content) measuring instruments and areometers

ISO 8310   Liquefied light hydrocarbons; temperature measurement in liquid gas containers; resistance thermometers and thermoelements

Guidelines of the European Union

93/43/EEC
Guideline of the Council dated 14th June food hygiene

83/128/EEC
Guideline of the Council dated 28th March 1983 for amendment of Guideline 76/764/EEC for the harmonization of the laws of the member countries concerning medical mercury-in-glass thermometers with maximum device
84/414/EEC
Guideline of the Commission dated 18th July 1984 for adaptation to the state of technical progress of the laws of the member countries concerning the laws of the member countries concerning medical mercury-in-glass thermometers with maximum device

International recommendations concerning measurements

OIML R 7   Medical mercury-in-glass thermometers with maximum device

OIML P 16   Guide for the taking of temperature measurements in practice

4.1.4.3 Non-German standards

Taiwan

CNS C 3082   Test methods for indicating resistance thermometers

CNS C 4198   Thermoelectric thermometers with indicator

CNS C 4199   Resistance thermometers with indicator

China

GB 1598   Platinum/rhodium-platinum thermocouples

GB 2614   Nickel-chromium/nickel-silicone thermocouples (IEC 584-1, IEC 584-2)

GB 2902   Platinum-rhodium 30%/platinum-rhodium 6% thermocouples

GB 2903   Copper/copper-nickel thermocouples

GB 2904   Nickel-chromium/gold-iron-copper/gold-iron thermocouples for low temperatures

GB/T 2974   Test methods for industrial thermocouples

GB 3413   Resistance thermometers

GB 3772   Platinum-10% rhodium/platinum thermocouples (IEC 584-1)

GB 4989   Thermocouples; thermal and compensating cables (IEC 584-3)

GB 4990   Thermocouples; thermal and compensating cables, alloy wire (IEC 584-3)

GB 4993   Nickel-chromium/copper-nickel thermocouples (IEC 584-1)

GB 4994   Iron-copper/copper-nickel thermocouples (IEC 594-1)

GB 5978   Platinum measuring resistor; measuring and testing method for thermometers

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France

NF B30-105	Measurement of upper and lower cooling temperature
NF B35-500 to 509	Laboratory instruments made of glass; solid stem and enclosed-scale thermometers
NF B37-003	Industrial thermometers
NF C42-342	Thermal and compensating cables for thermocouples, composition, material properties, production tests

Great Britain

BS 1041 P.2 Section 2.1	Temperature measurement, expansion thermometers, guide to the selection and use of liquid-in-glass thermometers
BS 1041 P.2 Section 2.2	Temperature measurement, expansion thermometers, guide to the selection and use of pointer thermometers
BS 1041 P.4	Temperature measurement, thermoelements
BS 1041 P.5	-,[2] guide to the selection and use of radiation pyrometers
BS 1041 P.7	-,[2] guide to the selection and use of temperature indicating equipment
BS 1900	Secondary reference thermometers
BS 2765	Temperature measuring elements and their protective tubes, size specification
BS 5074	Long and short solid stem thermometers for precision applications, specification
BS 5471	Specification for thermometers for use with areometers for alcohol

Italy

UNI 6429	Precision laboratory thermometers made of glass, with filling (liquid filling), design characteristics
UNI 6430	-,-,[2] long type, solid
UNI 6431	-,-,[2] short type, solid
UNI 6432	-,-,[2] long type, with internal scale
UNI 6433	-,-,[2] short type, with internal scale
UNI 6885	General use of thermometers made of glass with filling, design characteristics

[2] Abbreviated form. See page 351 for explanation.

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UNI 6886	-,-,[2] solid type
UNI 6887	-,-,[2] internal scale type
UNI 6888	Calorimetric thermometers, design characteristics
UNI 6889	-,[2] solid type
UNI 6890	-,[2] internal scale type
UNI 6891	Thermometers with adjustable gap (with internal scale), design characteristics
UNI 6892	-,[2] dimensions
UNI 6893	Glass thermometers with filling, test and inspection procedures
UI 9009	Industrial expansion and bimetal thermometers with dial indicator, nominal width, dimensions and mounting variants
UNI 9010	Industrial expansion, bimetal and glass thermometers with metal casing with dial indicator, accuracy classes
UNI 9011	-,[2] units and measure and measuring ranges
UNI 9012	-,[2] application limit value
UNI 9013	Industrial expansion and bimetal thermometers with dial indicator, scale division and numbering
UNI 9014	Industrial expansion, bimetal and glass thermometers with metal casing with dial indicator and design characteristics
UNI 9015	Industrial expansion and bimetal thermometers with dial indicator, degree scales and inscription for single scale dials
UNI 9112	-,[2] mounting position and relational graphic illustrations
UNI 7937	Thermometers with platinum resistor, marking and static characteristic
UNI 4768	Thermoelements, calibration comparison method
UNI 5008	Thermometers for industrial use and thermometers for refrigerating plants on ships, standard types
UNI 5009	Industrial thermometers for ships and thermometers with single encapsulation
UNI 5010	-,[2] with double encapsulation

[2] Abbreviated form. See page 351 for explanation.

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UNI 5011   -,[2)] with double encapsulation with a raised container

UNI 5012   -,[2)] with metal cases

UNI 5013   -, glass thermometers

UNI 5014   -,[2)] complete container for glass thermometers

UNI 5015   -, raised container complete for glass thermometers

UNI 5016   -,[2)] with single encapsulation, container, plug, capsule, slotted nut and lid

UNI 5017   -,[2)] with double encapsulation and a glass container

UNI 5018   -,[2)] with double encapsulation and a raised glass container

UNI 5019   -,[2)] with metal case container, sleeve and slotted nut

UNI 5020   -,[2)] with single or double encapsulation, graduated glasses

UNI 5021   -,[2)] with double encapsulation, sleeve with protective tube

UNI 5022   -,[2)] with double encapsulation internal and external

UNI 5023   -,[2)] with double encapsulation, screw nut, lid, slotted nuts and springs

UNI 5024   -,[2)] glass thermometers, plug with chain

UNI 5025   -,[2)] guidelines for the arrangement of thermometer holders and thermometers

UNI 5026   Low-temperature thermometers for ships

UNI 5027   -,[2)] encapsulation, glass and disks

UI 5028   Industrial thermometers and low-temperature thermometers for ships, technical conditions for glass for thermometers

India

IS 2806   Test method for measuring with electric resistance thermometers

Israel

SI 867   Medical mercury-in-glass thermometers

[2)] Abbreviated form. See page 351 for explanation.

Japan

JIS C 1601   Thermoelectric thermometers with indicator

JIS C 1603   Resistance thermometers with indicator

JIS Z 8705   Methods for taking temperature measurements with liquid-in-glass thermometers

JIS Z 8706   Methods for taking temperature measurements with optical pyrometers

JIS Z 8707   Method for taking temperature measurements with filled systems (spring thermometers with remote control) and bimetal thermometers

JIS Z 8710   General conditions for taking temperature measurements

Canada

CGSB CAN/CGSB-14.5-M88
     Thermometers with self-indication and bimetal, standard industrial design

Norway

NS 5507   Industrial glass thermometers with V-shaped case

NS 5508   Submersible thermometer tubes for industrial thermometers

NS 5509   Glass thermometers for industrial thermometers

Austria / Portugal / Spain

The majority of products are manufactured and delivered in accordance with DIN standards.

Saudi Arabia

SSA 154   Methods for the calibration of medical mercury thermometers

SSA 155   Medical mercury thermometers

U.S.A.

ANSI/ASHRAE 41.1   Standard methods for taking temperature measurements

ANSI/ASME PTC 19.3   Temperature measurements

API RP 550 -   Temperature, process and control instruments
Part 1, Section 3   for temperature for use in refineries

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Russia

GOST 112   Meteorological glass thermometers

GOST 302   Medical maximum thermometers made of glass

GOST 2888   Maximum thermometers made of glass for veterinary medicine

GOST 13646   Mercury thermometers made of glass for precision measurements

GOST 8624   Manometric thermometers of GSP

GOST 16920   Manometric temperature converters of GSP

GOST 14002   Temperature and temperature difference relay transmitters of GSP; general resistance thermal converters of GSP

GOST ED16651 Resistance thermal converters of GSP

GOST 12855   Mercury contact thermometers made of glass

GOST 23125   Temperature limit monitoring indicators

GOST 3044   Thermoelectric converters; calibration tables

4.1.5 Electrical temperature measuring instruments

4.1.5.1 German standards

DIN 13402   Medical electrical thermometers; definitions, requirements, tests

DIN 43701 Part1 Electrical switchboard instruments; technical terms of delivery; general conditions

DIN 43712   Measurement and control; electrical temperature sensors; wires for thermocouples

DIN 43714   -, -, -; -;[2)] compensating and thermal cables for thermoelements

DIN 43720   -, -, -; -;[2)] metal protective tubes for thermoelements

DIN 43721   -, -, -;[2)] electrical thermometers, mineral insulated thermoelement cables and mineral insulated thermoelements

DIN 43722   Thermocouples; Part 3: Thermal cables and compensating cables; limit deviations and identification system (modified version of IEC 584-3)

[2)] Abbreviated form. See page 351 for explanation.

DIN 43724   Measurement and control; electrical thermometers, ceramic protective tubes and holding rings for thermoelements

DIN 43725   -, -, -;[2] electrical temperature sensors; insulating tubes for thermocouples

DIN 43729   -, -, -;[2] electrical thermometers, connection heads for thermoelements and resistance thermometers

DIN 43732   -, -, -; -;[2] thermocouples for thermoelements

DIN 43733   -, -, -; -;[2] straight thermoelements without replaceable insert

DIN 43734   -, -, -; -;[2] stop flange for thermoelements and resistance thermometers

DIN 43735   -, -, -; -;[2] inserts for thermoelements

DIN 43762   -, -, -; -;[2] inserts for resistance thermometers

DIN 43763   -, -, -; -;[2] metal protective tubes for thermometers with insert

DIN 43764   -, -, -; -;[2] thermometers without fixture with replaceable insert

DIN 43765   -, -, -; -;[2] screw-in thermometers with G 1/2 screw-in thread

DIN 43766   -, -, -; -;[2] screw-in thermometers with G 1 screw-in thread

DIN 43767   -, -, -; -;[2] weld-in thermometers

DIN 43770   Electrical temperature measuring instruments; survey of straight thermoelements and resistance thermometers

DIN 43771   Measurement and control; electrical temperature sensors; thermometers with short response times

DIN 43772 Part 1   Control systems; metal protective tubes and neck tubes for industrial glass thermometers, pointer thermometers, thermoelements and resistance thermometers; survey of protective tube/thermometer arrangements

DIN 43772 Part 2   -; -, -, -,[2] dimensions

DIN 43783 Part 1   Electrical measuring resistors; direct current measuring resistors, reference: GSG

DIN 43801 Part 1   Electrical measuring instruments; spiral springs, dimensions

DIN 43802 Part 2   Line scales and pointers for indicating electrical measuring instruments; general rules

[2] Abbreviated form. See page 351 for explanation.

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DIN 43802 Part 3   -;[2] types and dimensions

DIN 43802 Part 4   -;[2] scale increments and numbering

DIN 43807   Measuring and control; electrical measuring instruments; terminal markings for switchboard instruments, panel meters and measuring converters for the measurement of power and the power factor

E DIN IEC 65B (CO)45   Dimensions of metal-protected thermometer
(=IEC 65B(SEC)76-1984) insets

DIN IEC 65B   Thermocouples; Part 1: thermoelectromotive force
(Sec) 175)   reference tables (IEC 65B (sec) 175: 1993)

DIN IEC 584 Part 1 Thermocouples; thermoelectromotive force reference tables

DIN IEC 584 Part 2 Thermocouples; thermoelectromotive force limit deviations

DIN IEC 751   Industrial platinum resistance thermometers and platinum measuring resistors

4.1.5.2 International standards

IEC 584   Thermocouples; Part 3: Thermal cables and
Part 3   compensating cables; limit deviations and identification system

International recommendations concerning measurements

OIML R 84   Sensors for resistance thermometers with measuring resistors made of platinum, copper or nickel (for industrial use)

4.1.5.3 Non-German standards

Great Britain

BS 1904   Sensors for platinum resistance thermometers for industrial use

BS 1041 Part 3   Temperature measurement, guide to the selection and use of resistance thermometers for commercial purposes

India

IS 2848   Specification for platinum resistance thermometer elements

IS 3636   Method of testing the temperature coefficient for precision resistance wires

Japan

JIS Z 8704   Electrical methods for taking temperature measurements

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[2] Abbreviated form. See page 351 for explanation.

France

NF R15-401	Thermometers with electrical transmission
NF R15-402	Road vehicles, thermal switches, tests and requirements
NF R15-403	Road vehicles, thermal switches, dimensions
NF C42-321	Electrical measuring instruments, thermocouples, thermoelectromotive force reference tables
NF C42-322	Thermocouples Part 2: Electromotive force limit deviations
NF C42-323	Electrical measuring instruments, identification of thermocouples
NF C42-330	Electrical measuring instruments, thermometric resistors on platinum, reference table and tolerances
NF C42-331	Temperature sensors with platinum resistor for stator windings. Execution, installation and use of temperature sensors installed between stator windings
UTE C46-201	Measurement and control in industrial processes, temperature probes with thermocouples

Russia

GOST 3044	Thermoelectrical converters; calibration tables
GOST 9871	Electrical contact mercury thermometers made of glass and thermocontrollers
GOST 12855	Mercury contact thermometers made of glass
GOST 12877	Platinum resistor low-temperature standard thermometers
GOST 14002	Temperature and temperature difference relay transmitters of GSP; general resistance thermal converts of GSP
GOST 14014	Digital measuring instruments and measurement converters for voltage, current, resistance
GOST 19875	High-speed electrical measurement recorders
GOST 23217	Analogue electrical measuring instruments with direct readings

4.1.6 Further standards and specifications concerning general measuring systems

4.1.6.1 German standards and specifications

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Standards

DIN 102	Reference temperature for measuring instruments and workpieces
DIN 1301 Part 1	Units, names, symbols
DIN 1301 Part 2	Units; sub-multiples and multiples for general use
DIN 1301 Part 3	Units; conversion factors for units no longer to be used
DIN 1302	General mathematical symbols and concepts
DIN 1304 Part 1	Symbols for use in formulae; general symbols for use in formulae
DIN 1304 Part 2	-;[2] symbols for use in formulae for meteorology and geophysics
DIN 1304 Part 3	-;[2] symbols for use in formulae for electrical power supply
DIN 1304 Part 5	-;[2] symbols for use in formulae for fluid mechanics
DIN 1304 Part 6	-;[2] symbols for use in formulae for electrical telecommunications
DIN 1304 Part 7	-;[2] symbols for use in formulae for electrical machines
DIN 1304 Part 8	-;[2] symbols for use in formulae for current rectifiers with semiconductor components
DIN 1305	Mass, measured value of weight, force, weight-force, weight, load; concepts
DIN 1314	Pressure, basic concepts
DIN 1306	Density; concepts, specifications
DIN 1319 Part 1	Basic concepts of measurement; general basic concepts
DIN 1319 Part 2	-;[2] concepts for the use of measuring equipment
DIN 1319 Part 3	-;[2] concepts for measurement uncertainty and for the assessment of measuring devices and measuring equipment
DIN 1319 Part 4	-;[2] dealing with uncertainties in the evaluation of measurements
DIN 1343	Reference conditions, standard conditions, standard volume; concepts and values
DIN 4751 Part 3	-;[2] closed heating installations with thermostatic safety requirements and flow pipe
DIN 1345	Thermodynamics; fundamental concepts

[2] Abbreviated form. See page 351 for explanation.

DIN 2401 Part 1   Components subjected to internal or external pressure; details of pressure and temperature; definitions, nominal pressure ratings

DIN 24312   Fluidics; pressure; values, definitions

DIN/VDE 1000   General guidelines for the safe design of
DIN 31000   technical products / Reference: GSG, MEDGV, NSRL

DIN 32811   Principles for the citation of reference materials in standards

DIN 43700   Measurement and control; measurement and control instruments for panel mounting, nominal and through-hole dimensions

DIN 43718   Measurement and control; front frames and front panels for measurement and control instruments; principal dimensions

DIN 43790   Basic rules for the design of line scales and pointers

DIN 43834   Measurement and control; fastening of measurement and control instruments for panel mounting; fastening element; fastening holes in the instrument

DIN 43835   Fastening for indicating instruments; fastening element, cone rivets on case, mounting arrangement

DIN 66034   Kilopond - Newton, Newton - kilopond, conversion tables

DIN 66037   Kilopond per square centimetre - bar, bar - kilopond per square centimetre; conversion tables

DIN 66038   Torr - millibar, millibar - torr, conversion table

DIN EN 19   Identification of industrial fittings for general use

VDI guidelines

VDI 2048   Measurement uncertainties during acceptance tests; principles

VDI/VDE 2600 Sheet 1   Metrology; lists of contents and complete keyword index of sheets 2 to 6

VDI/VDE 2600 Sheet 2   -;[2] basic concepts

VDI/VDE 2600 Sheet 3   -;[2] equipment-related concepts

VDI/VDE 2600 Sheet 4   -;[2] concepts for describing the characteristics of measuring instruments
VDI/VDE 2600 Sheet 5   -;[2] concepts for explaining the mode of operation of measuring instruments

VDI/VDE 2600 Sheet 6   -;[2] nomenclature of measuring instruments

[2] Abbreviated form. See page 351 for explanation.

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VDI/VDE 2620 Sheet 2   Propagation of error limits in measurements; examples of the propagation of errors and error limits

VDI/VDE 2635 Sheet 1   Strain foil gauges with metal grid; characteristic values and test conditions

Federal German statutory and administrative regulations

Calibration Law   Law concerning weights and measures

EichAnwVwV   Guideline for testing and monitoring in accordance with the Calibration Law and the Calibration Regulation (Calibration instructions - General directives)

MessEinh   Law concerning units in measuring

FlGasThermoEichVwV   General administrative regulation for the calibration of measuring instruments; calibration instructions, testing of liquid-in-glass thermometers)

EichZustV SL   Regulation concerning areas of responsibility for measurement and calibration

4.1.6.2 International standards and specifications

Guidelines of the European Community

71/316/EEC
Guideline of the Council dated 26th July 1971 for the harmonization of the laws of the member countries concerning common specifications for measuring instruments and for measuring and testing procedures

80/181/EEC
Guideline of the Council dated 20th December 1979 for the harmonization of the laws of the member countries concerning units of measurement and for the annulment of Guideline 71/354/EEC

83/575/EEC
Guideline of the Council dated 26th October 1983 for the amendment of Guideline 71/316/EEC for the harmonization of the laws of the member countries concerning common specifications for measuring instruments and for measuring and testing procedure

85/1/EEC
Guideline of the Council dated 18th December 1984 for the amendment of Guideline 80/181/EEC for the harmonization of the laws of the member countries concerning units of measurement

87/355/EEC
Guideline of the Council dated 25th June 1987 for the amendment of Guideline 71/316/EEC for the harmonization of the laws of the member countries concerning common specifications for measuring instruments and for measuring and testing procedures

89/617/EEC
Guideline of the Council of 27th November 1989 for the amendment of Guideline 80/181/EEC for the harmonization of the laws of the member countries concerning units of measurement

International standards

ISO 1000   SI units and stipulations for the use of their multiples and a number of other units

ISO 4399   Fluidic systems and components; connections and related components; nominal pressures

4.1.6.3 Non-German standards

China

GB 1242   Electrical measuring instruments

GB 11161   Electrical measuring instruments, dials

GB/T 13283   Accuracy classes of measuring and indicating instruments for industrial process measurements and checks

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U.S.A.

UL 913   Intrinsically safe instruments and their apparatus for use in potentially explosive areas class I; II and III, section 1

4.1.7 Standards and specifications with contents applying to safety

German standards

DIN 4751 Part 1 Water heating installations; open and closed physically protected heating installations with flow temperatures up to 120°C, safety equipment

DIN 4751 Part 2 -;[2] closed, thermostatically protected heating installations with flow temperatures up to 120°C; safety equipment

DIN 4751 Part 3 -;[2] closed, thermostatically protected heating installations with flow temperatures up to 95°C, 50 kW heat output, with forced circulation boilers; safety equipment

DIN 16006[1]   Pressure measuring instruments with Bourdon tube; safety requirements and testing

DIN 16007[1]   Pressure measuring instruments with elastic pressure-responsive element for air compressors and air compressor plants; safety requirements and testing

DIN 31001 Part 1 Safety requirements for the design of technical equipment; protecting devices; definitions, safety distances for adults and children, reference: GSG, MEDGV

DIN VDE 1000   General guidelines for the safe design of technical
DIN 31000   equipment, reference: GSG, MEDGV, NSRL

DIN VDE 0170/0171 Part 1 Electrical apparatus for potentially explosive atmospheres; general
=DIN EN 50014   requirements, German version of EN 50014: 1992

DIN VDE 0170/0171 Part 2 -;[2] oil immersion "o",
=DIN EN 50015   German version of EN 50015: 1994

DIN VDE 0170/0171 Part 3 -;[2] pressurised apparatus "p",
=DIN EN 50016   German version of EN 50017: 1994

DIN VDE 0170/0171 Part 4 -;[2] powder filling "q" (VDE
=DIN EN 50017   specification for flame-proof and explosion-proof equipment)

DIN VDE 0170/0171 Part 5 -;[2] flame-proof enclosure "d" (VDE
=DIN EN 50018   specification for flame-proof and explosion-proof equipment)

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[1] These standards are being replaced by European Standards DIN EN 837-1 to 3.
[2] Abbreviated form. See page 351 for explanation.

DIN VDE 0170/0171 Part 6   -;[2] increased safety "e" (VDE
=DIN EN 50019   specification for flame-proof and explosion-proof equipment)

DIN VDE 0170/0171 Part 7   -;[2] intrinsic safety "i" (VDE
=DIN EN 50020   specification for flame-proof and explosion-proof equipment)

VBG regulations

VBG 15   Welding, cutting and allied processes

VBG 15DA   Instructions for implementation of the accident prevention regulations

VBG 15   Compressors

VBG 18   Compressed air vessels on water vehicles

VBG 20   Refrigerating plants, heat pumps and cooling equipment

VBG 61   Gases

VBG 62   Oxygen

GUV accident prevention code

GUV 3.8   Accident prevention regulations for welding, cutting and allied processes,
                    with instructions for their implementation

GUV 9.8   Accident prevention regulations with instructions for their implementation

GUV 9.9   Accident prevention regulations for gases

GUV 19.9   Guidelines for the use of liquid gas

Federal German statutory and administrative regulations

TechArbmG   Law concerning technical equipment (Equipment safety law)

TechArbmG/PrüfstRL   Provisions, guidelines and notes for test centres in accordance with
                                  Section 3 Paragraph 4 of the law concerning technical equipment

TechArbmGV1   First directive dealing with the law concerning technical equipment

TechArbmGV6   Directive dealing with the equipment safety law and with the amendment
                                  of the pressure vessel directive; Article 1: 6th directive dealing with the
                                  equipment safety law (directive dealing with the marketing of simple pressure
                                  vessels - 6th GSGV)

TRD 110 Annex 1   Guidelines for the component testing of valves and fittings

[2] Abbreviated form. See page 351 for explanation.

DVGW G 490	Technical rules for the building and equipment of gas pressure control systems with inlet pressures of over 100 mbar up to and including 4 bar
DVGW G 491	Technical rules for the building and equipment of gas pressure control systems with inlet pressures of over 4 bar up to and including 100 bar, planning, manufacture, installation, testing, commissioning
DVGW G 493	Procedures for issuing a DVGW certificate for manufacturers of gas pressure control systems and gas measurement systems

Regulations concerning drink dispensing systems
Regulations concerning the technical requirements to be met by drink dispensing systems

Regulation concerning electrical systems in hazardous areas (ElexV)

Regulation concerning systems for the storage, decanting and conveyance of combustible liquids on land (Regulation concerning combustible liquids - VbF)

Regulation concerning boiler systems (DampfkV)

Regulation concerning pressure vessels, compressed gas containers and filling installations (Pressure vessel regulation - DruckbehV)

Regulation concerning acetylene installations and calcium carbide stocks (Acetylene regulation - AcetV)

4.1.8 Further information is to be found in:

- Internationale Gewindeübersicht, Kennbuchstaben, Profile und Bezeichnungen von Gewinden in Normen verschiedener Länder, available from: Beuth-Verlag, D-10772 Berlin

- International Dictionary of Metrology, available from: Beuth-Verlag, D-10772 Berlin

- Stahlschlüssel, available from Verlag Stahlschlüssel WEGST GMBH & Co., D-71672 Marbach

- DECHEMA-Tabellen, available from: DECHEMA, D-60486 Frankfurt

4.1.9 Contact addresses for standards and specifications

AD codes of practice
Publisher: Vereinigung der Technischen Überwachungs-Vereine e.V., P.O.Box 10 38 34, D-45038 Essen
Distributor: Beuth-Verlag GmbH, D-10772 Berlin

Mining works engineering specifications (BB)
Publisher and distributor: Steinkohlenbergbauverein, Franz-Fischerweg 61, D-45307 Essen

German standards
Publisher: DIN Deutsches Institut für Normung e.V., D-10772 Berlin
Distributor: Beuth-Verlag GmbH, D-10772 Berlin

DIN VDE standards
Publisher: DIN Deutsches Institut für Normung e.V., D-10772 Berlin and
Verband Deutscher Elektrotechniker (VDE) e.V., Stresemannallee 15, D-60596 Frankfurt
Distributor: VDE-Verlag GmbH, P.O.Box 12 23 05, D-10591 Berlin

DKD guidelines
Publisher and distributor: Physikalisch-Technische Bundesanstalt, P.O.Box 33 45,
D-38023 Braunschweig

DKV work sheets for heating and refrigeration
Publisher: Deutscher Kälter- und Klimatechnischer Verein, Pfaffenwaldring 10,
D-70569 Stuttgart
Distributor: Hütling Fachverlage, D-69018 Heidelberg

Calibration regulations (EO)
Publisher: Physikalisch-Technische Bundesanstalt (PTB)
Distributor: Deutscher Eichverlag, Hopfengarten 21, 38102 Braunschweig

GUV accident prevention code
Publisher: Bundesverband der Unfallversicherungsträger der öffentlichen Hand e.V., Fockensteinstrasse
1, D-81539 Munich
Distribution: By local insurance offices (ask the publisher)

OIML recommendations
Publisher: Organisation Internationale de metrologie Legale, Rue Turgot 11, F-75009 Paris
Distributor: Physikalische-Technische Bundesanstalt, P.O.Box 33 45, D-38023 Braunschweig

PTB test regulations
Publisher and distributor: Physikalische-Technische Bundesanstalt, P.O.Box 33 45,
38023 Braunschweig
Federal German statutory and administrative regulations
Sources are quoted in the respective official organ of announcement.

Guidelines of the European Community
The guidelines of the European Community are announced in the Official Journal of the European
Community

KTA safety regulations
Publisher: Kerntechnisher Ausschuss c/o Gesellschaft für Reaktorsicherheit (GRS),
P.O.Box 10 01 49, D-38201 Salzgitter
Distributor: Carl Heymanns Verlag KG, Luxemburger Str. 449, D-50939 Cologne.
The technical regulations of the KTA (no drafts) are announced in the Federal German Gazette.

4 Appendix and tables

SEB steel-iron works engineering specifications
Publisher: Verein Deutscher Eisenhüttenleute, Sohnstrasse 65, D-40237 Düsseldorf
Distributor: Verlag Stahleisen mbH, P.O.Box 10 51 64, D-40042 Düsseldorf.
Drafts available from the publisher.

PTB technical guidelines
Publisher and distributor: Physikalishe-Technische Bundesanstalt, P.O.Box 33 45,
D-38023 Braunschweig

TRbF technical regulations for flammable liquids
Publisher: Federal German Minister of Labour and Social Affairs (BMA), P.O.Box 14 02 80,
D-53107 Bonn.
The technical regulations for flammable liquids are announced in the Federal German Gazette.
Individual copies of TRbF published by VdTÜV are available in DIN A4 format from Carl Heymanns
Verlag.

TRGL technical regulations for high-pressure gas lines
Publisher: Federal German Minister of Labour and Social Affairs (BMA), P.O.Box 14 02 80,
D-53107 Bonn.
The technical regulations for high-pressure gas lines are announced in the Federal German
Gazette.
Individual copies of TRbF published by VdTÜV are available in DIN A4 format from Carl Heymanns
Verlag.

TRAC technical regulations for acetylene systems and calcium carbide stocks
Publisher: Federal German Minister of Labour and Social Affairs (BMA), P.O.Box 14 02 80,
D-53107 Bonn.
The technical regulations for acetylene systems are announced in the Federal German Gazette.
Individual copies of TRbF published by VdTÜV are available in DIN A4 format from Carl Heymanns
Verlag.

Technical guidelines concerning tanks
Publisher: Federal Republic of Germany

The technical guidelines concerning tanks are announced in the Commercial Gazette.

VBG regulations
Publisher: Hauptverband der gewerblichen Berufsgenossenschaften e.V., D-53754 St. Augustin
Distributor: Carl Heymanns Verlag KG, Luxemburger Str. 449, D-50939 Cologne

VDA specification sheets
Publisher and distributor: Verband der Automobilindustrie e.V.,
P.O.Box 17 05 63, D-60079 Frankfurt

VDI guidelines
Publisher: Verein Deutscher Ingenieure e.V., P.O.Box 10 11 39, D-40002 Düsseldorf
Distributor: Beuth-Verlag GmbH, D-10772 Berlin

VG standards
Publisher: Federal German Bureau of Military Equipment and Procurement,
P.O.Box 73 60, D-56057 Koblenz
Distributor: Beuth-Verlag GmbH, D-10772 Berlin

VDMA specification sheets
Publisher: Verband Deutscher Maschinen- und Anlagenbau e.V.
P.O.Box 71 08 64, D-60498 Frankfurt
Distributor: Beuth-Verlag GmbH, D-10772 Berlin

VdTÜV codes of practice and resolutions
Publisher: Vereinigung der Technischen Überwachungs-Vereine e.V.,
P.O.Box 10 38 34, D-45038 Essen
Distributor: Verlag TÜV Rheinland GmbH, P.O.Box 90 30 60, D-51123 Cologne

Explanation of abbreviated form

The symbols -; / -, / -,-, etc. are used for better clarity.
Each symbol stands for a section of text in the **previously cited unabbreviated** standard.
Sections of text are separated by a comma or semicolon.

Example:

DIN 16102   Pointer for pressure gauges, class 0.6; 160 and 250 mm case diameter

DIN 16103   -, accuracy classes 0.2 and 0.3; 250 mm case diameter

Here the symbol "-," stands for the section of text "Pointer for pressure gauges,".

4.2 Tables and overviews

4.2.1 Tables of legal units

Length, area and volume

Dimension (Symbol)	SI unit	Multiples of SI unit	Inch based unit	Multiples of inch based units	Other units
plane angle ($\propto$, β, γ)	rad (radian)	μrad mrad	rad (radian)	μrad mrad	" (second) ' (minute) gon (Gon) °(degree)
solid angle (Ω, ω)	sr (steradian		sr (steradian		
Length (l)	m (meter)	nm μm mm cm km	in. (inch)	μ in. ft. yd. mi.	
Wavelength (λ)	m• (meter)	pm nm μm mm	in. (inch)	μ in.	
Area (A, S)	m¥ (sq. meter)	mm¥ cm¥ dm¥ km¥	in.¥ (sq. inch)	ft.¥ yd.¥ mi.¥	
Volume (V)	m¥ (cubic meter)	mm¥ cm¥ dm¥	in.¥ (cubic inch)	ft.¥ yd.¥	l (liter) p (pint) g (gallon)

Time and space

Dimension (Symbol)	SI unit	Multiples of SI unit	Inch based unit	Multiples of inch based units	Other units
Time (t)	s (Second)	ns μs ms ks	s (Second)	ns μs ms ks	min (minute) h (hour) d (day)
Period duration, duration of oscillation (T)	s	ns μs ms	s	ns μs ms	
Frequency (F,)	Hz (Hertz)	kHz MHz GHz THz	Hz (Hertz)	kHz MHz GHz THz	
Rotational speed (n)	s		s		
Angular velocity (ω, Ω)	rad/s		rad/s		
Speed (v, u)	m/s		m/s		m/h km/h ft./h mi./h
Acceleration (a)	m/s•		m/s•		

Dimension (Symbol)	SI unit	Multiples of SI unit	Inch based unit	Multiples of inch based units	Other units

Mechanical

Dimension (Symbol)	SI unit	Multiples of SI unit	Inch based unit	Multiples of inch based units	Other units
Mass (m)	kg (kilogram)	µg mg ms g Mg	lb. (pound)	ou. (ounce) G (gross) t (ton)	t (metric ton)
Mass per unit length (m')	kg/m	mg/m	lb./ft.	ou./ft.	
Density (ρ, ρ$_m$)	kg/m¥	g/cm¥ kg/dm¥ Mg/m¥	lb./ft.¥	ou./ft.¥	t/m¥ kg/l
Moment of inertia (J)	kg ¥ m¥		lb. ¥ ft.¥		
Force (F)	N (Newton)	µN mN kN MN	lb. (f)	ou. (f) t (f)	
Torque (M)	N ¥ m	N ¥ m mN ¥ m kN ¥ m MN ¥ m	lb. (f) ¥ ft.	ou.(f) ¥ ft. t (f) ¥ ft.	
Impulse (p, I)	kg ¥ m/s		lb. ¥ ft./s		
Angular momentum (L)	kg ¥ m¥/s		lb. ¥ ft.¥/s		
Pressure (p)	Pa (Pascal) bar (Bar)	Pa mPa mbar kPa MPa GPa	PSI (lbs./in.¥)	ou./in.¥	in. H2O ft. H2O

Dimension (Symbol)	SI unit	Multiples of SI unit	Inch based unit	Multiples of inch based units	Other units
Stress (σ)	N/m•, Pa	kPa N/mm• MPa GPa			
Dynamic Viscosity (η)	Pa • s	mPa • s			
kinematic Viscosity (ν)	m•/s	mm•/s			
Surface tension (σ, γ)	N/m	mN/m			
Work energy (W, A) (E, W)	J (Joule)	mJ kJ MJ GJ TJ			eV (electron volt) keV MeV GeV - W • h kW • h MW • h GW • h TW • h
Power (P)	W (Watt)	µW mW kW MW GW			

Dimension (Symbol)	SI unit	Multiples of SI unit	Inch based unit	Multiples of inch based units

Electricity and magnetism

Dimension (Symbol)	SI unit	Multiples of SI unit	Inch based unit	Multiples of inch based units
Electrical charge (Q)	C (Coulomb)	pC nC µC mC kC		
Density of surface charge (σ)	C/m•	µC/m• mC/m• kC/m• C/cm• C/mm• MC/m•		
Density of volume charge (ρ, η)	C/m•	µC/m• mC/m• kC/m• C/cm• MC/m• C/mm•		
Electric flux (ψ, ψ_e)	C	mC kC MC		
Electric flux density (D)	C/m•	µC/m• mC/m• kC/m• C/cm•		
Electric polarization (P)	C/m•	µC/m• mC/m• kC/m• C/cm•		
Electric dipol moment (p, p_e)	C • m			
Electric potential (φ) Electric voltage (U)	V (Volt)	µV mV kV MV		

Dimension (Symbol)	SI unit	Multiples of SI unit	Inch based unit	Multiples of inch based units
Electric current (I)	A (Ampere)	pA nA µA mA kA MA		
Specific current density (J,S)	A/m•	kA/m• A/cm• A/mm• MA/m•		
Electric current density (A, a)	A/m	A/cm A/mm kA/m		
Magnetomoti force (V)	A	mA k/A MA		
Magnetic field strength (H)	A/m	A/cm A/mm kA/m		
Magnetic flux (φ)	Wb (Weber)	mWb		
Magnetic flux density (B)	T (Tesla)	nT µT mT		
Magnetic vector potential (A)	Wb/m	Wb/mm kWb/m		
Inductivity (L)	H (Henry)	pH nH µH mH		
Permeability (µ)	H/m	nH/m MH/m		

Dimension (Symbol)	SI unit	Multiples of SI unit	Inch based unit	Multiples of inch based units
Electric field strength (E)	V/m	μV/m mV/m V/cm V/cm kV/m MV/m		
Electric capacity (C)	F (Farad)	aF pF nF μF mF		
Permissivity Dielectric constant (ε)	F/m	pF/m nF/m μF/m		
Magenti-zation (m, H)	A/m	A/mm kA/m		
Magentic polarization (J, B)	T	mT		
Electro-magnetic moment (m)	A • m•			
Magnetic resistance (R)	H^{-1}			
Magnetic conductance (Λ)	H			

Dimension (Symbol)	SI unit	Multiples of SI unit	Inch based unit	Multiples of inch based units
Electric resistance (R)	Ω (Ohm)	μΩ m k m M G T		
Electric conductivity (G)	S (Siemens)	μS mS kS		
Specific electric resistance, volume resistance (ρ)	Ω • m	n μ m Ω k M G		
Electric conductivity (γ, σ, χ)	S/m	kS/m MS/m		
Reactance (X)	Ω	m k M		
Susceptance (B)	S	μS mS kS		
Impedance (IZI)	Ω	m k M		
Admittance (|Y|)	S	μS mS kS		
Power (P)	W	nW μW mW kW MW GW TW		

Dimension (Symbol)	SI unit	Multiples of SI unit	Inch based unit	Multiples of inch based units

Thermodynamics and heat transfer

Dimension (Symbol)	SI unit	Multiples of SI unit	Inch based unit	Multiples of inch based units
Thermodynamic temperature (T, Q)	K (Kelvin)	mK		
Temperature difference $\Delta T = \Delta t = \Delta \vartheta$	K	mK		
Temperature Celsius (t, ϑ)	°C (degree-celsius)			
Thermal volume coefficient of expansion $(a^\vee, g)$	K^{-1}			
Heat quantity (Q) Internal energy	J	mJ kJ MJ GJ TJ		
Heat flow (Φ, Q)	W	KW		
Thermal conductivity (λ)	W/(m · K)			
Heat transfer coefficient (α, h)	W/(m· · K)			
Heat capacity (C)	J/K	kJ/K		
Specific heat capacity (c)	J/(kg · K)	kJ/(kg · K)		
Entropy (S)	J/K	kJ/K		
Specific entropy (s)	J/(kg · K)	kJ/(kg · K)		

4.2.2 Conversion factors for commonly used pressure units

4.2.2.1 SI units – Technical units (metric)

from \ to	SI units						Technical units					
	bar	mbar	μbar	Pa	kPa	MPa	mmHg	mmH_2O	mH_2O	kg/mm^2	kg/cm^2	atm
1 bar	1	10^3	10^6	10^5	100	0.1	750.064	$10.1972 \cdot 10^3$	10.1972	$10.1972 \cdot 10^{-3}$	1.01972	0.986923
1 mbar	10^{-3}	1	10^3	100	0.1	$0.1 \cdot 10^{-3}$	$750.064 \cdot 10^{-3}$	10.1972	$10.1972 \cdot 10^{-3}$	$10.1972 \cdot 10^{-6}$	$1.01972 \cdot 10^{-3}$	$0.986923 \cdot 10^{-3}$
1 μbar	10^{-6}	10^{-3}	1	0.1	$0.1 \cdot 10^{-3}$	$0.1 \cdot 10^{-6}$	$750.064 \cdot 10^{-6}$	$10.1972 \cdot 10^{-3}$	$10.1972 \cdot 10^{-6}$	$10.1972 \cdot 10^{-9}$	$1.01972 \cdot 10^{-6}$	$0.986923 \cdot 10^{-6}$
1 Pa	10^{-5}	0.01	10	1	10^{-3}	10^{-6}	$7.50064 \cdot 10^{-3}$	$101.972 \cdot 10^{-3}$	$101.972 \cdot 10^{-6}$	$101.972 \cdot 10^{-9}$	$10.1972 \cdot 10^{-6}$	$9.86923 \cdot 10^{-6}$
1 kPa	0.01	10	$10 \cdot 10^3$	10^3	1	10^{-3}	7.50064	101.972	$101.972 \cdot 10^{-3}$	$10.1972 \cdot 10^{-6}$	$10.1972 \cdot 10^{-3}$	$9.86923 \cdot 10^{-3}$
1 MPa	10	$10 \cdot 10^3$	$10 \cdot 10^6$	10^6	10^3	1	$7.50064 \cdot 10^3$	$101.972 \cdot 10^3$	101.972	$101.972 \cdot 10^{-3}$	10.1972	9.86923
1 mmHg	$1.33322 \cdot 10^{-3}$	1.33322	$1.33322 \cdot 10^3$	133.322	$133.322 \cdot 10^{-3}$	$133.322 \cdot 10^{-6}$	1	13.5951	$13.5951 \cdot 10^{-3}$	$13.5951 \cdot 10^{-6}$	$1.35951 \cdot 10^{-3}$	$1.31579 \cdot 10^{-3}$
1 mmH_2O	$98.0665 \cdot 10^{-6}$	$98.0665 \cdot 10^{-3}$	98.0665	9.80665	$9.80665 \cdot 10^{-3}$	$9.80665 \cdot 10^{-6}$	$73.5561 \cdot 10^{-3}$	1	10^{-3}	10^{-6}	$0.1 \cdot 10^{-3}$	$96.7841 \cdot 10^{-6}$
1 mH_2O	$98.0665 \cdot 10^{-3}$	98.0665	$98.0665 \cdot 10^3$	$9.80665 \cdot 10^3$	9.80665	$9.80665 \cdot 10^{-3}$	73.5561	10^3	1	10^{-3}	0.1	$96.7841 \cdot 10^{-3}$
1 kg/mm^2	98.0665	$98.0665 \cdot 10^3$	$98.0665 \cdot 10^6$	$9.80665 \cdot 10^6$	$9.80665 \cdot 10^3$	9.80665	$73.5561 \cdot 10^3$	10^6	10^3	1	100	96.7841
1 kg/cm^2	0.980665	$0.980665 \cdot 10^3$	$0.980665 \cdot 10^6$	$98.0665 \cdot 10^3$	98.0665	$98.0665 \cdot 10^{-3}$	735.561	$10 \cdot 10^3$	10	0.01	1	0.967841
1 atm	1.01325	$1.01325 \cdot 10^3$	$1.01325 \cdot 10^6$	$101.325 \cdot 10^3$	101.325	$101.325 \cdot 10^{-3}$	760	$10.3323 \cdot 10^3$	10.3323	$10.3323 \cdot 10^{-3}$	1.03323	1

Further relationships:

1 Pa	$= 1\ N/m^2$	1 mmHg	= 1 Torr
1 hPa	= 1 mbar		

4.2.2.2 SI units – Technical units (inch based)

		SI units						ANSI units			
	to / from	bar	mbar	µbar	Pa	kPa	MPa	psi	ft H$_2$0	in. H$_2$0	in. Hg
SI units	1 bar	1	10^3	10^6	10^5	100	0.1	14.50377	33.4553	401.463	29.52998
	1 mbar	10^{-3}	1	10^3	100	0.1	$0.1 \cdot 10^{-3}$	$14.50377 \cdot 10^{-3}$	$33.4553 \cdot 10^{-3}$	$401.463 \cdot 10^{-3}$	$29.52998 \cdot 10^{-3}$
	1 µbar	10^{-6}	10^{-3}	1	0.1	$0.1 \cdot 10^{-3}$	$0.1 \cdot 10^{-6}$	$14.50377 \cdot 10^{-6}$	$33.4553 \cdot 10^{-6}$	$401.463 \cdot 10^{-6}$	$29.52998 \cdot 10^{-6}$
	1 Pa	10^{-5}	0.01	10	1	10^{-3}	10^{-6}	$0.1450377 \cdot 10^{-3}$	$0.334553 \cdot 10^{-3}$	$4.01463 \cdot 10^{-3}$	$0.2952998 \cdot 10^{-3}$
	1 kPa	0.01	10	$10 \cdot 10^3$	10^3	1	10^{-3}	0.1450377	0.334553	4.01463	0.2952998
	1 MPa	10	$10 \cdot 10^3$	$10 \cdot 10^6$	10^6	10^3	1	$0.1450377 \cdot 10^3$	$0.334553 \cdot 10^3$	$4.01463 \cdot 10^3$	$0.2952998 \cdot 10^3$
ANSI units	1 psi	$68.94757 \cdot 10^{-3}$	68.94757	$68.94757 \cdot 10^3$	$6.894757 \cdot 10^3$	6.894757	$6.894757 \cdot 10^{-3}$	1	2.30666	27.6799	2.036020
	1 ft H$_2$O	$29.8907 \cdot 10^{-3}$	29.8907	$29.8907 \cdot 10^3$	$2.98907 \cdot 10^3$	2.98907	$2.98907 \cdot 10^{-3}$	$433.5275 \cdot 10^{-3}$	1	12	0.8826709
	1 in. H$_2$0	$2.49089 \cdot 10^{-3}$	2.49089	$2.49089 \cdot 10^3$	$0.249089 \cdot 10^3$	0.249089	$0.249089 \cdot 10^{-3}$	$36.12729 \cdot 10^{-3}$	$83.3333 \cdot 10^{-3}$	1	$73.55591 \cdot 10^{-3}$
	1 in. Hg	$33.86389 \cdot 10^{-3}$	33.86389	$33.86389 \cdot 10^3$	$3.386389 \cdot 10^3$	3.386389	$3.386389 \cdot 10^{-3}$	0.4911542	1.132925	13.59510	1

Further relationships:

1 Pa = 1 N/m^2

1 psi = 1 lbf/in.^{2}

1 mmHg = 1 Torr

4.2.2.2 SI units – Technical units (inch based)

from \ to	Technical units (metric)						Technical units (inch based)			
	kg/mm^2	kg/cm^2	atm	mmHg	mH_2O	mmH_2O	psi	ft H_2O	in. H_2O	in. Hg
1 kg/mm^2	1	100	96.7841	73.5561 $\cdot 10^3$	10^3	10^6	1.422334 $\cdot 10^3$	3.28084 $\cdot 10^3$	39.3701 $\cdot 10^3$	2.895902 $\cdot 10^3$
1 kg/cm^2	0.01	1	0.967841	735.561	10	10 $\cdot 10^3$	14.22334	32.8084	393.701	28.95902
1 atm	10.3323 $\cdot 10^{-3}$	1.03323	1	760	10.3323	10.3323 $\cdot 10^3$	14.69595	33.8985	406.782	29.92125
1 mmHg	13.5951 $\cdot 10^{-6}$	1.35951 $\cdot 10^{-3}$	1.31579 $\cdot 10^{-3}$	1	13.5951 $\cdot 10^{-3}$	13.5951	19.33672 $\cdot 10^{-3}$	44.6032 $\cdot 10^{-3}$	0.535239	39.36996 $\cdot 10^{-3}$
1 mH_2O	10^{-3}	0.1	96.7841 $\cdot 10^{-3}$	73.5561	1	10^3	1.422334	3.28084	39.3701	2.895902
1 mmH_2O	10^{-6}	0.1 $\cdot 10^{-3}$	96.7841 $\cdot 10^{-6}$	73.5561 $\cdot 10^{-3}$	10^{-3}	1	1.422334 $\cdot 10^{-3}$	3.28084 $\cdot 10^{-3}$	39.3701 $\cdot 10^{-3}$	2.895902 $\cdot 10^{-3}$
1 psi	703.0695 $\cdot 10^{-6}$	70.30695 $\cdot 10^{-3}$	68.04596 $\cdot 10^{-3}$	51.71507	0.7030695	703.0695	1	2.30666	27.6799	2.036020
1 ft H_2O	304.8 $\cdot 10^{-6}$	30.48 $\cdot 10^{-3}$	29.4998 $\cdot 10^{-3}$	22.4199	0.3048	304.8	433.5275 $\cdot 10^{-3}$	1	12	0.8826709
1 in. H_2O	25.4 $\cdot 10^{-6}$	2.54 $\cdot 10^{-3}$	2.45834 $\cdot 10^{-3}$	1.86833	25.4 $\cdot 10^{-3}$	25.4	36.12729 $\cdot 10^{-3}$	83.3333 $\cdot 10^{-3}$	1	73.55591 $\cdot 10^{-3}$
1 in. Hg	345.3156 $\cdot 10^{-6}$	34.53156 $\cdot 10^{-3}$	33.42096 $\cdot 10^{-3}$	25.4	0.3453156	345.3156	0.4911542	1.132925	13.59510	1

Left vertical label for top six rows: Technical units (metric). Left vertical label for bottom four rows: Technical units (inbased).

Further relationships:

1 Pa = 1 N/m^2

1 psi = 1 $lbf/in.^2$

1 mmHg = 1 Torr

1 ft. H_2O = 1 ft. W.C. (water column)

4.2.3 Refrigerants

National regulations in many countries, including the United States, have resulted in a halt in production of fully halogenated chloro-fluorohydrocarbons (CFCs). The prohibition of CFCs covers the refrigerants R12, R22 and R502 which used to be the most frequently used refrigerants.

Substitute for R12

The substitution product R134a is already in wide use.

Substitute for R502

a) The production of R115, the fully halogenated component CFC component in R502, has since been discontinued. R502 has been used traditionally for a wide range of temperature of up to -40°F.

b) The refrigerant manufacturers have also developed mixtures with similar characteristics to R502 for replacement products while considering their compatibility and the expense involved as replacements in existing units.

Substitute for R22

a) The Montreal Protocol Concerning the Discontinuation of Ozone Threatening Refrigerants was supplemented in November 1992 in Copenhagen by the addition of HCFC (like R22) to the list of those refrigerants whose use is to be gradually reduced in upcoming years.

b) Appropriate EC guidelines are currently being drawn up. There are signs that HCFC refrigerants will be banned in the near future in many countires for certain types of new plants. Mixtures are also planned to replace the refrigerant R22.

At the moment the substitute refrigerants are assigned as follows:

R12   replaced by   **R134a**
R22   replaced by   **R407C**, R410A, R404A, (R32)
R502 replaced by   **R404A**, R407A, R507, R125, (R32), (R143a)

The substitute refrigerants printed in bold type are the ones favored so far. Those in brackets are combustible and are therefore used only as mixture components.

The relationship between temperature and absolute vapor pressure in the saturation state is shown in the vapor tables of the refrigerant producers.

The absolute vapor pressure values are converted using the equation $pe = p_{abs} - p_{amb}$, where pe = overpressure, p_{abs} = absolute pressure and p_{amb} = atmospheric pressure at 1.01325 bar in accordance with DIN 1343.

Refrigerants R407A and R407C are aceotropic mixtures with a wide boiling range of approx. 5 K (temperature slide). The range limits of the temperature slide are the bubble point and the dew point, and may require two temperature scales. The refrigerant producers supply the corresponding vapor tables. Both range limits may be printed on the dial, depending on the user's specifications.

The public's growing awareness of refrigerants is also reflected in higher requirements, with increased scrutiny of environmental aspects. Certainly, the ozone depleting potential of the substitute materials must be zero. They must further minimize the greenhouse effect, result in a low energy consumption of refrigerating plants and thus reduce the overall global warming.

4.2.4 pH values of various solutions at 68°F (20°C)

Solution	Concentration			
	Normality	g/l	weight %	pH
Formic aid	0.1	4.6	0.46	2.3
Ammonia	1	17.0	1.7	11.6
Ammonia	0.1	1.7	0.17	11.1
Ammonia	0.01	0.17	0.02	10.6
Malic acid	0.1	6.7	0.67	2.2
Cider				2.9-3.3
Benzoic acid	0.01	1.2	0.12	3.1
Beer				4.0-5.0
Prussic acid	0.1	2.7	0.23	5.1
Borax	0.1	10.0	1	9.2
Boric acid	0.1	2.1	0.21	5.2
Ferric hydroxide	saturated			9.5
Acetic acid	1	60.0	6.0	2.4
Acetic acid	0.1	6.0	0.6	2.9
Acetic acid	0,01	0.6	0.06	3.4
Urine	saturated			4.8-8.4
Potassium hydroxide	1	56.0	5.4	14.0
Potassium hydroxide	0.1	5.6	0.58	13.0
Potassium hydroxide	0.01	0.56	0.06	12.0
Lime	saturated			12.4
Calcium carbonate				9.4
Calcium cyanate	0.1	6.5	0.65	11.0
Carbonic acid, saturated				3.8
Lemonade				2.0-4.0
Magnesium hydroxide	saturated			10.5
Milk				6.6-7.6
Lactic acid	0.1	9.0	0.90	2.4
Sodium bicarbonate	0.1	8.4	0.84	8.4
Sodium hydroxide	1	40.0	3.9	14.0
Sodium hydroxide	0.1	4.6	0.4	13.0
Sodium hydroxide	0.01	0.40	0.04	12.0
Sodium carbonate	0.1	5.3	0.53	11.6
Sodium phosphate	0.1	5.5	0.55	12.0
Sodium silicate	0.1	6.1	0.61	12.6
Oxalic acid	0.1	4.5	0.43	1.6
Phosphoric acid	0.1	3.3	0.33	1.5
Pure water				7.0
Hydrochloric acid	1	36.5	3.5	0.1
Hydrochloric acid	0.1	3.7	0.36	1.1
Hydrochloric acid	0.01	0.37	0.04	2
Sulphuric acid	1	49.0	4.8	0.3
Sulphuric acid	0.1	4.9	0.49	1.2
Sulphuric acid	0.01	0.49	0.05	2.1

Solution	Concentration			
	Normality	g/l	weight %	pH
Hydrogen sulphide	0.1	1.7	0.17	4.1
Sulphurous acid	0.1	4.1	0.41	1.5
Sea water				8.3
Wine				2.8 to 3.8
Wine vinegar				2.4 to 3.4
Tartaric acid	0.1	7.5	0.75	2.2
Citric acid	0.1	6.4	0.64	2.2

4.2.5 Boiling and melting point of various process fluids at 29.90 "Hg (1013.25 mbar)

Fluid or gas	Boiling Point		Melting Point	
	¡C	¡F	¡C	¡F
Ethyl alcohol	78.3	172.94	-114.5	-174.10
Ammonia	-33.4	-28.12	-77.7	-107.86
Ethyl ether	34.5	94.10	-116.3	-177.34
Acetone	56.1	132.98	-94.3	-137.74
Acetylene	-83.6	-118.48	-81	-113.80
Benzol	80.1	176.18	5.5	41.90
Bromium	58.8	137.84	-7.3	18.86
Chlorine	-35	-31.00	-103	-153.40
Chloroform	61.2	142.16	-63.5	-82.30
Acetic acid	118	244.40	16.7	62.06
Fluorine	-188	-306.40	-220	-364.00
Glycerine	290	554.00	16	60.80
Helium	-268.9	-452.02	-	-
Hydrogen iodide	-36	-32.80	-51	-59.80
Sodium chloride	1413	2575.40	770	1418.00
Carbon oxide	-191.5	-312.70	-205	-337.00
Carbon dioxide	-78.5	-109.30	-56	-68.80
Air (without CO_2)	-194	-317.20	-	-
Methane	-161.7	-259.06	-182.5	-296.50
Methyl alcohol	64.5	148.10	-98	-144.40
Naphtalene	218	424.40	80.1	176.18
Sodium chloride	1440	2624.00	802	1475.60
Nitrobenzol	210.9	411.62	5.7	42.26
Paraffine	300	572.00	54	129.20
Phosphorus	280	536.00	44.1	111.38
Mercury	356.95	674.51	-38.83	-37.89
Oxygen	-182.97	-297.35	-218.83	-361.89
Carbon disulphide	46.25	115.25	-112	-169.60
Sulphuric acid	-	-	10.5	50.90
Nitrogen	-195.81	-320.46	-210.02	-346.04
Toluol	110.7	231.26	-95	-139.00
Water	100	212.00	0	32.00
Hydrogen	-252.78	-423.00	-259.2	-434.56

4 Appendix and tables

4.2.6 Density of process fluids

Designation	Reference temperature		Density g/cm•
	°C	°F	
Ammonia water	18	64	0.88
Ether	18	64	0.72
Ethyl alcohol	18	64	0.79
Ethylen	-103.5	-154	0.568
Aniline	20	68	1.022
Argon, liquid	-185.9	-303	1.404
Ehtylene glycol	20	68	1.113
Ammonia	0	32	0.639
Ammonia	20	68	0.61
Benzene	18	64	0.68 to 0.81
Benzol	18	64	0.879
Beer	-	-	1.02 to 1.04
Chlorine, liquid	-35	-31	1.558
Chloroform	18	64	1.489
Acetic acid	18	64	1.049
Petroleum crude	20	68	0.7 to 1.04
Fluorine	-188	-306	1.11
Fluoric acid	13.6	56	0.99
Aviation lubricants	20	68	0.893
Glycerine	18	64	1.26
Caustic potash solution 10 %	18	64	1.09
Caustic potash solution 50 %	18	64	1.51
Sodium chloride solution 5 %	18	64	1.03
Sodium chloride solution	18	64	1.19
Carbon dioxide, liquid	-181	-294	1.6267
Carbon dioxide	0	32	0.925
Mineral oils	20	68	0.89 to 0.96
Sea water	15	59	1.026
Methanol	4	39	0.8
Whole milk	15	59	1.028
Skim milk	15	59	1.032
Methyl alcohol	18	64	0.81
Naphta	19	66	0.76
Sodium hydroxide 10 %	18	64	1.11
Sodium hydroxide 50 %	18	64	1.53
Olive oil	18	64	0.915

Designation	Reference temperature		Density g/cm•
	°C	°F	
Petroleum	18	64	0.76 to 0.86
Mercury	20	68	13.546
Mercury	0	32	13.5951
Rape seed oil	15	59	0.91 to 0.92
Rape seed oil	15	59	0.91
Nitric acid 25 %	18	64	1.151
Nitric acid 100 %	18	64	1.52
Hydrochloric acid 10 %	18	64	1.048
Hydrochloric acid 40 %	18	64	1.199
Sulphuric acid 25 %	18	64	1.18
Sulphuric acid 100 %	18	64	1.833
Sulphuric acid, fluiding	18	64	1.835
Spindle oil	20	68	0.871
Turpentine oil	18	64	0.855
Transformer oil	20	68	0.866
Water, distilled	0	32	0.99984
Water, distilled	4	39	0.99997
Water, distilled	20	68	0.99823
Water, distilled	25	77	0.99707
Water, distilled	100	212	0.95838
Wine	-	-	0.99 to 1.0
Hydrogen peroxide	0	32	1.465

4.2.7 Types of enclosure ratings for cases (NEMA and IP)

NEMA Ratings
The NEMA Rating system is a standard primarily used in North America for rating enclosures. The table below shows the equivalent IP ratings. NEMA standards meet or exceed the IP ratings listed, but the reverse cannot be assumed.

NEMA Rating	Description	Equivalent IP Rating
1	GENERAL PURPOSE. Intended for use indoors	IP 10
2	GENERAL PURPOSE. Intended for use indoors with additional drip protection	IP 11
3 & 3S	GENERAL PURPOSE WEATHER-RESISTANT. Intended for use outdoors with protection from windblown dust, rain, and sleet, and undamaged by the formation of ice.	IP 54
3R	GENERAL PURPOSE WEATHER-RESISTANT. Intended for use outdoors with protection from falling rain and sleet, and undamaged by the formation of ice.	IP 14
4 & 4X	GENERAL PURPOSE WEATHERPROOF. Intended for use indoors or outdoors with protection from washdown environment and corrosion resistance.	IP 65
5	GENERAL PURPOSE DUST-TIGHT. Intended for use indoors or outdoors with protection from dust provided by gaskets.	IP 52
6 & 6P	GENERAL PURPOSE SUBMERSIBLE. Intended for use indoors or outdoors with protection from occasional submersion.	IP 67
7	HAZARDOUS. Intended for indoor use in Class I, Groups A, B, C, and D environments per NFPA rating system.	- -
8	HAZARDOUS. Intended for indoor or outdoor use in Class I, Groups A, B, C, and D environments per NFPA rating system.	- -
9	HAZARDOUS. Intended for indoor or outdoor use in Class II, Groups E, F, and G environments per NFPA rating system.	- -
12 & 12K	INDUSTRIAL USE. Intended for use in industrial applications with protection from dust and noncorrosive liquid drip.	IP 52
13	INDUSTRIAL USE. Intended for use in industrial applications with protection from dust, spraying water, oil, and noncorrosive liquid drip.	IP 54

IP Ratings

The IP Rating system (or **I**nternational **P**rotection Code) is a worldwide standard for rating enclosures. The rating is written as IP-"XY" where X and Y are replaced by the first and second numeral as listed in the tables below.

Degree of protection from contact or foreign bodies

First number	Brief Description
0 1 2	No special protection. Generally not used for pressure or temperature instruments
3	Protected against solid objects > 2.5 mm in diameter.
4	Protected against solid objects > 1.0 mm in diameter.
5	Dust protected
6	Dust-tight

Degree of water protection

Second number	Brief description
0	No special protection. Generally noted used for pressure or temperature instruments.
1	Protected against dripping water
2	Protection against dripping water when case is tilted up to 15°
3	Protected against spraying water
4	Protected against splashing water
5	Protected against a water jet
6	Protected against heavy jet spray
7	Protected against limited submersion
8	Protect against continuous submersion

4.2.8   Common materials of pressure gauges

Preferred materials for particular pressure gauge components

Component	Preferred material type				
	Unalloyed or low-alloyed steel	High-alloyed steel	Light metals and their alloys	Copper and wrought copper alloy	Other materials
Sockets		316 stainless steel		Brass	Monel
Measuring elements	Carbon steel	316 stainless steel		Copper alloys	Monel, Duratherm, Ni Span C, titanium
Separating Diaphragms or Protective Coatings		316 stainless steel			Hastelloy, Monel, Incoloy, Inconel, Ag, Au, Ta, Zr, ECTFE, PTFE, PFA
Thin-film sensors		PH 17-4 stainless steel			
Cases	Steel	304 stainless steel	Aluminum	Brass	ABS, Polyamid, Polycarbonate
Flanges	Steel	300 series stainless steel	Aluminum	Brass	Hastelloy, Monel
Movements		300 series stainless steel		Brass	PTFE, POM
Dials			Aluminum		ABS
Pointer hubs			Aluminum	Brass	ABS
Pointer arms			Aluminum	Brass	ABS
Windows					Safety glass, flat glass, acrylic, polycarbonate
Gaskets & o-rings					EPDM, EPM, FKM, NBR, PUR

Material descriptions:

Designation	Material
Non-corrosion resistant metal alloys	
Aluminum	Al 99
Copper-alloy	Copper-zinc alloy or copper-tin alloy with 60 to 97% copper
Carbon steel	Carbon steel
Special metal alloys	
Hastelloy	Nickel-molybdenum alloy
Monel	Nickel-copper alloy
Ni Sapn C	Iron-nickel-alloy with 41 to 43.5% Ni, 4.9 to 5.575% Cr, 2.2 to 2.75% Ti and other small percentages of Al, C, Mn, Si, S and P
Nonmetallic materials	
ABS	Acrylo-nitrile-butadiene-styrene Tradename example: Terluran
E-CTFE	Ethylen-chlorotrifluoroethylene Tradename example: Halar
PC	Polycarbonate Tradename example: Lexan
PFA	Perfluoralkoxy-copolymer Tradename example: Teflon PFA
PMMA	Polyacrylate Tradename example: Plexiglas
POM	Polyoxymethylene Tradename example: Ultraform
PTFE	Polytetrafluoroethylene Tradename example: Teflon
Flat glass	Standard flat glass
Safety glass	Laminated safety glass

4.2.9 Comparison of corrosion-resistant steels between international standards

U.S.A. ASTM A276	Germany DIN 17440/17441	France NF A 35-574	United Kingdom BS970/4	Italy UNI 6901	Sweden MNC 900	Spain UNE 36-016	Russia GOST 5632	Japan JIS G 4303	European Standard EURONORM-88	European Material Number (DIN)
434	X 6 CrMo 17 1	Z 8 CD 17.01	434 S 17	X 8 CrMo 17	2325	F.3116-X6CrMo 17 1		SUS 434	X 8 CrMo 17	1.4113
430 F	X12 CrMoS 17	Z 10 CF 17		X 10 CrS 17	2383	F.3117-X10CrS 17		SUS 460 F	X 14 CrS 17	1.4104
431	X 20 CrNi 17 2	Z 15 CN 16-02	431 S 29	X 16 CrNi 16	2321	F.3427-X19CrNi 17 2	20 Ch17 N2	SUS 431	X 21 CrNi 17	1.4057
303	X 10 CrNiS 18 9	Z 8 CNF 18-09	303 S 21	X 10 CrNiS 18 09	2346	F.3508-X10CrNiS 18-09	O K H18 N10 E	SUS 303	X 10 CrNiS 18 9	1.4305
304 H	X 5 CrNi 18 10	Z 6 CN 18-09	304 S 15	X 5 CrNi 18 10	2332	F.3504-X5CrNi 18 10	08 Ch18 N10	SUS 304 H	X 6 CrNi 18 10 kt	1.4301
305	X 5 CrNi 18 12	Z 8 CN 18-12	305 S 19	X 8 CrNi 19 10		F.3513-X8CrNi 18-12	06 Ch18 N11	SUS 305	X 8 CrNi 18 12	1.4303
304 L	X 2 CrNi 19 11	Z 2 CN 18-10	304 S 12	X 2 CrNi 18 11	2333	F.3503-X2CrNi 18-10	03 Ch18 N11	SUS 304 L	X 3 CrNi 18 10	1.4306
321	X 6 CrNiTi 18 10	Z 6 CNT 18-10	321 S 18	X 6 CrNiTi 18 11	2337	F.3523-X6CrNiTi 18-10	09 Ch18 N10 T	SUS 321	X 6 CrNiTi 18 10	1.4541
347	X 6 CrNiNb 18 10	Z 6 CNNb 18-10	347 S 17	X 6 CrNiNb 18 11	2338	F.3524-X6CrNiNb 18-10	08 Ch18 N12 B	SUS 347		1.4550
316	X 5 CrNiMo 17 12 2	Z 6 CND 17-11	316 S 13	X 5 CrNiMo 17 12	2347	F.3534-X5CrNiMo 17 12 2		SUS 316	X 6 CrNiMo 17 12 2	1.4401
316 L	X 2 CrNiMo 17 13 2	Z 2 CND 17-12	316 S 11	X 2 CrNiMo 17 12	2348	F.3533-X2CrNiMo 17 13 2		SUS 316 L	X 3 CrNiMo 17 12 2	1.4404
316 Ti	X 6 CrNiMoTi 17 12 2	Z 6 CNDT 17-12	320 S 18	X 6 CrNiMoTi 17 12	2350	F.3535-X6CrNiMoTi 17 12 2	10 Ch17 N13 M2 T		X 6 CrNiMoTi 17 12 2	1.4571
316 Cb	X 6 CrNiMoNb 17 12 2	Z 6 CND Nb 17-12	318 S 17	X 6 CrNiMoNb 17 12		F.3536-X6CrNiMoNb 17 2 2	08 Ch16 N13 M2 B		X 6 CrNiMoNb 17 13 2	1.4580
316	X 5 CrNiMo 17 13 3	Z 6 CND 18-12-03	316 S 31	X 5 CrNiMo 17 13	2343	F.3534-X5CrNiMo 17 12 2		SUS 316	X 6 CrNiMo 17 13 3	1.4436
316 L	X2 CrNiMo 18 14 3	Z 3 CND 17-12-03	316 S 11	X 2 CrNiMo 17 13	2353	F.3533-X2CrNiMo 17 13 2	03 Ch17 N 14 M3	SUS 316 L	X 3 CrNiMo 17 13 3	1.4435
317 L	X 2 CrNiMo 18 16 4	Z2 CND 19-15-04	317 S 12	X 2 CrNiMo 18 16	2367	F.3539-X2CrNiMo 18 16 4		SUS 317 L	X 3 CrNiMo 18 16 4	1.4438
304 LN	X 2 CrNiN 18 10	Z 3 CN 18-07 AZ	304 S 61	X 2 CrNiN 18 11	2371	F.3541-X2CrNiN 18 10		SUS 304 LN	X 3 CrNiN 18 10	1.4311
316 LN	X 2 CrNiMoN 17 12 2	Z 3 CND 17-11 AZ	316 S 61	X 2 CrNiMoN 17 12		F.3542-X2CrNiMoN 17 12 2		SUS 316 LN	X 3 CrNiMoN 17 12 2	1.4406
316 LN	X 2 CrNiMoN 17 13 3	Z 3 CND 17-12 AZ	316 S 63	X 2 CrNiMoN 17 13	2375	F.3543-X2CrNiMoN 17 13 3		SUS 316 LN	X 3 CrNiMoN 17 13 3	1.4429

4.2.10 Corrosion resistance table

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Abietic acid	1	1	0	0	0	0	0	0	0
Acetanilide	0	0	0	0	0	0	0	0	0
Acetic acid	2	1	1	0	2	1	1	0	0
Acetic aldehyde	0	1	0	0	0	0	0	0	0
Acetonacetic ester		1	0	0	0	0	0	0	0
Acetoncyanhydrine		1			0	0	0	0	0
Acetone	0	0	0	0	0	0	0	0	0
Acetonphenetidine	0	2	0	0	0	0	0	0	0
Acetonophenone	0	0	0	0	0	0	0	0	0
Acetylacetone			0		0	0	0	0	0
Acetylcelulose	1	2	0	0	0	0	0	0	0
Acetylchloride	2	1	1	1	0	0	0	0	
Acetylene (Cu < 65%)	0	0	0	0	0	0	0	0	0
Acetylsalicyclic acid		2	0	0	0	0	0	0	0
Acetylthiopropene		1	0					0	0
Acid blends	2	1	1	0	2	2	2	0	1
Acid pit water			0		2	2			
Acid sodium sulphate			0	0					
Acridine		0	0				0	0	
Acroleine	0	0	0	0	1	1	0	0	0
Acrylic acid ethylester				0					
Acrylic silicate	0	0	0	0	0	0	0		
Acrylonitrile	0	0	0	0	0	0	0	0	0
Adipic acid		0	0	0	0	0	0	0	
Aktivin (chloramine T)			0						
Alcane-sulfonic acid	2	2	0	0		1	0	0	
Alcoholic beverages	0	2	0	0	0	0	0	0	0
Alizarine		0	0	0	0	0	0	0	
Alkyd resins	0	1	0	0	0	0	0	0	0
Alkylaryl sulfonates	0	0	0	0	0	0	0	0	0
Alkylation		0	0		0	0			
Alkylchloride ether		1			1	1	0	0	
Alkyinaphthalinesulfonic acid		1				0	0	0	
Allyl amine	2	0	0	0				0	
Allyl chloride	0	0	0	1	0	0	0	0	
Allyl sulphide	1	0	0						
Allylic alcohol	1	0	0	0	0	0	0	0	0

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta- lum	Tita- nium
Aloe		2	0		0	0	0	0	
Aluminium acetate		2	0		0	0	0	0	0
Aluminium alkyle		0	0		0	0	0		
Aluminium chlorate			0	0	0	0	0	0	
Aluminium chloride	2	1	1	0	1	1	0	0	1
Aluminium ethylate		0	0		0	0	0	0	
Aluminium fluoride		1		0	0	0	0		
Aluminium formiate		1	0	0	0	0	0	0	0
Aluminium melts	2	0	2	2	2	2			
Aluminium nitrate		2	0	0	0	0	0		0
Aluminium oxide and hydroxide	0	0	0	0	0	0	0	0	0
Aluminium salts				0					
Aluminium silicofluoride	0	2	0		0	0	0		
Aluminium sulphate	2	2	1	0	2	1	0	0	0
Amines and amination	2	1	0	0	0	0	0	0	
Amino acid blends		2	0		0	0	0	0	
2-aminoanthrachinone		0	0		0	0	0		
p-aminobenzene		1		0	1		0	0	
m-aminobenzenesulfonic acid		0	0	0	0	0	0	0	
p-aminobenzenesulfonic acid		0	0	0	0	0	0	0	
Aminobenzoic acid		0	0	0	0	0	0	0	0
5-amino-2-oxybenzoic acid		0	0	0	0	0	0	0	
m -aminophenole		0	0		0	0	0	0	
c- and p-aminophenole		0	0		0	0	0	0	
Aminoplastics	0	1	0	0	0	0	0	0	
2-aminopyridine	1	1	0		0	0	0		
p-aminosalycyclic acid		1	0	0	0	0	0	0	
Ammoniac-ammonium hydroxide	1	0	0	0	1	1	0	1	0
Ammonium acetate		1	0		0	0	0		
Ammonium alum			1						
Ammonium bicarbonate	2	0	0	0	2	2			
Ammonium bromide		1	0	0	0	0	0	0	
Ammonium carbonate			0						
Ammonium carbonate		0	0	0					
Ammonium carbonate-, carbomat	2	1	0	0	2	0		0	
Ammonium chloride	2	1	0	0	0	0	0	0	0
Ammonium citrate		1	0	0	0	0	0	0	0
Ammonium difluoride			0		1	1			

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Ammonium diphosphate	1	1	0	0	0	0	0	0	0
Ammonium disulphite		1	0	0	0	0	0	0	
Ammonium fluoride	1	1	1	1	1	1			
Ammoniumfluorsilicate		1	0		0	0	0		
Ammonium formiate		1	0	0	0	0	0	0	0
Ammonium molybdate		0	0	0					
Ammonium monophosphate	1	1	0	0	0	0	0	0	
Ammonium nitrate	2	1	0	0	2	2	0	0	0
Ammonium oxalate		1	0		0	0		0	
Ammonium perchlorate		1	0				0	0	
Ammonium persulphate	2	2	1		0	2		0	
Ammonium phosphate				0	1	1		0	
Ammonium picrate		1	0		0	0	0		
Ammonium rhodanide	2	1	0	0	0	0	0		
Ammonium sulphaminate	0	0	0	0	0	0	0	0	0
Ammonium sulphate	2	1	0	0	0	0	0	0	0
Ammonium (poly)-sulphide	2	1	0	0	0	0	0		
Ammonium sulphite		1	0	0	2	2	1	0	
Ammonium tungstate		0	0	0	2	2			
Amyl acetate	0	1	0	1	0	0	0	0	0
Amyl alcohol	0	1	0	0	0	0	0	0	0
Ayml amine	2	1	0	0	0	0	0		
Amyl borate				0					
Amyl chloride (without water)	0	1	1		0	1	0	0	
Amyl laurate	0	0	0	0	0	0	0	0	0
Amyl mercaptane		1	0		0	0	0		
Amyl nitrate		0	0						
Amyl nitrite		0	0						
p-amyl phenole	0	1	0		0	0	0	0	0
Amyl propionate	0	1	0		0	0	0	0	0
Aniline	1	1	0	0	1	1	1	0	0
Aniline black	0	1	0	0	0	0	0		
Aniline hydrochloride	2	2		0	2	2	0		
Aniline sulphate		2	0	0	0	0	0		
Aniline sulphite	1	1	0	0			0		
Anis aldehyde	0	1	0	0	0	0	0	0	0
Anisidine	0	1	0	0	0	0	0	0	
Anis oil	0	1	0	0	0	0	0	0	0

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Anisol	0	0	0	0	0	0	0	0	0
Anthracene, oil	0	0	0	0	0	0	0	0	0
Antimony chloride		2	2		0	0	0	0	
Antimony melt			2	2					
Antrachinone	0	0	0		0	0	0	0	
Antrachinonesulfone acides		1	0	0	0	0	0	0	
Apple juice, -pulp	2	2	0	0	0	0		0	
Aqua regia	2	2	2	0	2	2	2	0	0
Aquasal sol.				0					
Arachic acid	1	1	0	0	0	0	0	0	
Aralene		1	0	0	0	0	0	0	0
Argon	0	0	0	0	0	0	0	0	0
Arsenic		1	0		1				
Arsenic acid, pentoxide	1	1	0	0	1	1	0	0	
Arsenous acids	2	2	0	0	0	0	0	0	
Arsenous chloride	2	1			0	0	0	0	
Arsenic trioxide		0	0	0	0	0	0		
Asordine				0					
Aspartic acid	2	0	0	0			0	0	
Asphalt	1	1	0		0	0	0		
ASTM oil 1,2,3				0					
Atmosphere (air)	0	1	0	0	0	0	0	0	0
Azobenzene	0	0	0	0	0	0	0	0	0
Azo yellow	1	2	0						
Bacitracine		2	0				0		
Baking powder	1	1	0	0	0	0	0	0	0
Barium carbonate	0	1	0	0					
Barium chlorate	0	1	0	0	0	0	0	0	
Barium chloride	2	1	0	0	1	1	0	0	0
Barium cyanide	2	0	0	0	0	2		2	
Barium hydroxide	0	0	0	0	0	0	0	0	
Barium nitrate	1	1	0	0	0		0		
Barium oxide		1	0			0	0		
Barium peroxide	2	1	1	0	1	1		2	
Barium salts				0					
Barium sulphate	0	0	0	0	0	0	0	0	0
Barium (poly)-sulphide	1	1	0	0	1	0		2	

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Basileum FG (TM)				0					
Batoxin (TM)				0					
Battery acid				0					
Beer	0	2	0	0	0	0	0	0	0
Bees' wax	0	1	0	0	0	0	0	0	0
Beer wort	0	0	0	0	0	0	0	0	0
Benzaldehyde	1	1	0	0	1	1	0	0	
1,2,4-benzaldehyde disulfonic acid		0	0	0	0	0	0	0	
Benzamide	2	1	0	0	0	0	0	0	0
Benzanthrene	0	0	0	0	0	0	0	0	
Benzine	0	1	0	0	0	0	0	0	0
Benzene	1	1	0	0	0	0	0	0	0
Benzene-1.3-disulfonic acid		1	0			0	0	0	
Benzene peroxide			0		0	0	0		
Benzene-sulfonic acid		1	0	0	1	0	0	0	
Benzidine	0	0	0	0	0	0	0	0	0
2.2-benzidine disulfonic acide	0	0	0	0	0	0	0		
Benzidine-3-sulfonic acid	0	0	0	0	0	0	0	0	0
Benzile	0	0	0	0	0	0	0	0	0
Benzilic acid	1	1	0	0	0	0	0		
Benzoic acid	1	1	0	0	0	1	0	0	0
Benzoic acid anhydride	0	2	0	0	0	0	0		
2-(4-benzylechloride)-benzoic acid	0	1	0	0	0	0	0	0	0
Benzoic acid sulfimide		1	0		0	0	0	0	
Benzoine		0	0		0	0	0		
Benzonitrile	0	0	0	0	0	0	0	0	0
1 .4-benzoquinone		1	0		0	0	0		
Benzotrichloride		1		2	0	0	0		
Benzotrifluoride		0	0		0	0	0		
o-benzoylbenzoic acid	0	0	0	0	0	0	0	0	
Benzylchloride		1		0	1	1	0	0	
Benzyl acetate		1	0		0	0	0	0	
Benzyl alcohol	0	1	0	0	0	0	0	0	
Benzyl amine		0	0		0	0	0		
Benzyl benzoate	0	0	0		0	0	0	0	
Benzyl butylphtalate	0	0	0	0	0	0	0	0	0
Benzyl cellulose		0	0	0	0	0	0	0	
Benzyl chloride	0	2	0		0	0	0	0	

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta- lum	Tita- nium
Benzyl ethylaniline	0	0	0	0	0	0	0	0	0
Benzyl phenol	0	1	0		0	0	0	0	
Benzyl salicylate	0	1	0	0	0	0	0	0	0
Benzyl sulfanil acid	0	1	0	0	0	0	0	0	0
Bergamot oil	1	1	0		0	0	0	0	
Beryllium chloride		1	1	0	1	1	0	0	
Beryllium fluoride	0	1	0		0	0	0		
Beryllium sulphate			0	0	0	0	0	0	
Bitumen		1	0	0	0	0	0		
Black iron ink			0						
Black Ive				0					
Bleaching liquid	2							0	
Blood	0	2	0	0	0	0	0	0	0
Borax	0		0	0					
Bordeaux liquor	1	1	0	0	0	0	0		
Boric acid	1	1	1	0	1	1	0	1	0
Borneol	0	2	0		0	0	0	0	0
Bornyl acetate	0	1	0		0	0	0	0	
Bornyl chloride	0				0	0	0	0	
Bornyl formiate			0		0	0	0	0	
Boron phosphate	1	1			2	2	2		
Boron trifluoride		1	0	0		0			
Brackish water	1	1			1	1			
Brake fluid	0	0	0	0	0	0	0	0	0
Brandy	1	1	0						
"Brindi" acid conc.				0					
Bromic acid	2	2	2		2	2			
Bromine	1	1	2	0	1	1	1	0	2
Bromine trifluoride		0	0		0	0		2	
Bromobenzene	0	1	0	0	0	0	0	0	0
Bromoform		1	0		0	0	0	0	
1.3-butadiene		1	0	0					
Butane	1	1	0	0	0	0	0		
Butane diol	0	1	0	0	0	0	0	0	
1 .4-butine-2-diol	0	1	0	0	0	0	0	0	0
Butter	2	2	0	0				0	0
Buttermilk	1	2	0	0	1	1		0	
Butyl acetate	1	1	0	1	1	1	0	0	0

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Butyl alcohol	0	1	0	0	0	0	0	0	0
Butylamine	2	1	0		0	0	0		
Butyl benzoate	0	0	0	0	0	0	0		
Butyl butyrate		1	0		0	0	0	0	
Butyl chloride		1	1		0	0	0	0	
Butylene	0	1	0	0	0	0	0	0	0
1.4-butylen-2-diol	0	0	0	0	0	0	0	0	0
n-butyl ether	0	0	0	0	0	0	0	0	0
Butyl glycolate	0	1	0	0	0	0	0	0	0
n-butyl glycol	0	0	0	0	0	0	0	0	0
Butyl mercaptane	2	1	0		0		0		
Butyl oxatale	0	1	0	0	0	0	0	0	
Butyl phenol (tertiary)	0	1	0		0	0	0		
Iso-butyl phosphate	0	1	0		0	0	0	0	
Butyl phthalate		1	0		0	0	0	0	
Butyl stearate	1	1	0	0	0	0	0	0	0
Butyl urethane		0	0		0	0	0	0	
Butyidehyde	0	1	0	0	0	0	0	0	0
Butyric acid	1	2	0	0	2	1	0	0	0
n-butyric acid anhydride	1	0		0	0	0	0		
Butyric acid chloride		1		1	0	0	0		
g-butyrolactone	0	1	0		0	0	0	0	0
Cadmium chloride		2	0	0	1		0	0	
Cadmium cyanide		2		0	2				
Cadmium melts	2	0	1	2					
Cadmium sulphate	0	1	0	0	0	0	0	0	
Caffeine	0	1	0	0	0	0	0	0	0
Calcium		0	0						
Calcium acetate	0	1	0	0	0	0	0	0	0
Calcium arseniate	0	0	0						
Calcium benzoate	0	1	0	0	0	0	0	0	0
Calcium bicarbonate	0	1	0	0	0	0	0	0	0
Calcium bisulphite	2	2	0	0	2	2	0	0	0
Calcium bromide	1	1	1	0	1	1	0	0	0
Calcium carbonate	0	1	0	0	0	0	0	0	0
Calcium chlorate	0	1	0	0	1	0	0		0
Calcium chloride	2	1	1	0	0	0	0	0	0

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Calcium chromate	0	0	0	0	0	0	0		
Calcium fluoride	0	0	0	0	0	0	0	2	
Calcium gluconate	0	0	0	0	0	0	0	0	0
Calcium hydride	0	0	0		0	0	0		
Calcium hydroxide	0	0	0	0	0	0	0	0	
Calcium hypochloride (+ calcium chloride)	2	1	1		1	1		0	0
Calcium lactate		1	0	0	0	0	0	0	0
Calcium nitrate	0	1	1	0	1	0	0		0
Calcium oxalate	0	1	0	0	0	0	0	0	
Calcium oxide	0	0	0		0	0	0		
Calcium permanganate		1	0	0	0	0	0		0
Calcium peroxide		1	0	0					
Calcium phosphate	0	1	0	0	0	0	0	0	0
Calcium rhodanide	0	1	1	0	0	0	0		
Calcium stearate	0	1	0	0	0	0	0	0	0
Calcium sulfaminate		0	0	0	0	0	0	0	0
Calcium sulphate	0	1	0	0	0	0	0	0	0
Calcium sulphide	2	0	0	0	1				
Calcium sulphite	1	1	0	0	1	1		0	0
Calcium tungstate			0	0	0	0	0		
Camphene	0	0	0	0	0	0	0	0	0
Camphor			0						
Camphor	0	0	0	0	0	0	0	0	0
Camphoric acid	0	2	0	0	0	0	0	0	0
d-camphor sulfonic acid		1	1	0	1	1	0	0	
n-capric acid	1	1	0	0	1	1	0	0	0
e-caprolactame		1	0		0	0	0		
Capronic acid	1	1	0	0	1	1	0	0	0
Capronic aldehyde	0	1	0	0	0	0	0	0	0
Caprylic acid	1	0	0	1	1	0	0	0	
Caprylic alcohol	0	1	0	0	0	0	0	0	0
Capsaicin (TM)		1	0		0	0	0		
Carbazole		0	0		0	0	0	0	0
Carbitol	0	0	0	0	0	0	0	0	0
Carbolic acid	1		0	0	1	1	0	0	0
Carbolineum	0	0	0	0	0	0	0	0	0
Carbolineum	0	0	0	0					

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta- lum	Tita- nium
Carbon dioxide	1	1	0	0	1	1	0	1	1
Carbonized mass		2		0		0	0		
Carbon monoxide	1	1	0	0	1	1	0	1	1
Carbon sulfide	1	0	0	0	0	1	0	0	0
Carbon tetrachloride	1	1	0	0	0	0	0		0
N -(4carboxyhenyl)-y-acid			0	0	0	0	0		0
Carnallite	1	1	0	0	0	0	0	0	0
Caro acid		2		0				0	
Carotene	0	0	0	0	0	0	0	0	0
Cascara	0	1	0	0	1				
Caseine			0	0	0	0	0	0	0
Cashew	0	1	0	0					0
Castor oil	0	1		0					
Cavit		2	0		0	0	0	0	0
Cesium chloride		1	1		0	0	0		
Cesium hydroxide		1	1		1	1			
Celluloid	0	1	0	0	0	0	0	0	0
Cellulose acetobutyrate	0	1	0		0	0	0	0	0
Cellulose ether		1	0	0					
Cellulose nitrate	0	1	0		0	0	0		
Cellulose paints	1	1	0	0	0	0	0	0	0
Cellulose tripropionate	0	1	0		0	0	0	0	0
Ceresine	0	0	0	0	0	0	0	0	0
Cerium chloride		1		0	0			0	
Cerium fluoride		1		0				0	
Cerium sulphate		1		0	0				
Cetylic alcohol	0	1	0		0	0	0	0	0
Chaulmooga acid	1	1	0	0	0	0	0		
Cheese			0						
Chloracetic acid	2	1	1	0	1	1	1	0	0
Chloramine	0	1	0	0	0	0	0		
Chloraminebenzoic acid		1	0	0	0	0	0	0	0
Chloramphenicol		2	0	0				0	0
Chloranile	0	0	0	0	0	0		0	0
Chloraniline	1	1	0		0	0		0	0
Chloranthraquinone		0	0		0	0	0	0	
Chlordane	1	1	0		0		0		
Chlorhydrine	1	1	0	0	0	0	0	0	

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta- lum	Tita- nium
Chloric acid	2	2	2	0	2	2		0	
Chlorinated water			1	0					
Chlorine	1	1	1	0	1	1	1	0	1
Chlorine alum				0					
Chlorine cresol	0	1	0		0		0	0	
Chlorine dioxide		1	1	0		0	2	0	
Chlorine diphenyl	0	0	0		0	0	0	0	
Chlorobenzene	0	1	0	0	0	1	0	0	0
Chlorobenzenetrifluoride		0	0		0	0	0		
Chlorobenzoic aldehyde		1	0	0	0	0	0	0	
Chloroethenebenzene		1	1		0	0	0	0	
Chloroform	1	1	0	0	0	0	0	0	0
Chloroformic acid ester	0	1						0	
4-chloro-2-nitraline		1	0		0	0	0		
Chloronitrobenzenes	1	0	0		0	0	0	0	0
4-chloronitrobenzene-3-sulfonic acid		1	0	0	1	0	0	0	
Chloronitrobenzoic acid		1	0	0	0	0	0	0	0
4-chloro-2-nitrophenol		1	0		0	0	0		
Chlorophenol	0	1	0		0	0	0	0	
Chlorophenoxyacetic acid		1	0	0	0	0	0	0	
Chlorophylle, Chlorophylline	0	0	0	0	0	0	0	0	0
Chloropikrine	1	0	0		0	0	0	0	
Chloroprene		1	0		0	0	0		
Chlorosilane		0	0		0	0	0	0	
Chlorosulfonic acid		1	1	0	1	1	0	0	0
Chlorotoluene	0	0	0	0	0	0	0	0	0
Chlorotoluidine	1	1	0		0	0	0		
Chlorotrifluoroethylene	0	1	0	2	0	0	0		
Chloroxylene	0	1	0		0	0	0	0	
Chocolate			0						
Cholesterin	0	0	0	0	0	0	0	0	0
Choline	2	1	0	0					
Choline chloride	2	1					0		
Chromic acid, oxide	2	1	0	0	2	2	2	0	0
Chromium alum	1	2	1	0	1	1	0	0	0
Chromium baths (galvanic)				0					
Chromium chloride		2	1	0	1		0	0	
Chromium fluoride	2	2				0		0	

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Chromium glucosate		0	0		0	0		0	0
Chromium nitrate			0	0					0
Chromium oxide, hydroxide	0	0	0	0	0	0	0	0	0
Chromium phosphate		1	0	0	0	0	0	0	
Chromium sulphate	1	2	1	0	1	1	0	0	
Chromyl chloride		0	0		0	0	0	0	0
Cider	1	2	0	0	0	0	0	0	
Citral	0	1	0	0	0	0	0	0	0
Citric acid	2	2	0		0	1		0	
Citronellal	0	1	0		0	0	0	0	0
Citronellol	0	1	0	0	0	0	0	0	0
Citrus fruit	1	2	0	0	1	1	0	0	0
Citrus oil	0	1	0	0	0	0	0	0	0
City gas	1	0	0	0	1	1	0	0	0
Clophene				0					
Clupanadioc acid	1	2	0	0	1	0	0	0	0
Cocaine	0	1	0	0	0	0	0	0	
Codeine	0	2	0	0				0	
Codein salts	0	2	1	0	0	0	0	0	
Cod-liver oil	1	1	0	0	0	0	0	0	0
Coffee	0		0		0	0			
Colza oil				0					
Concrete	0	1	0	0	0	0	0	0	
Coniferylic alcohol	0	1	0	0	0	0	0	0	0
Copal	0	1	0		0	0	0	0	0
Copper acetate	1	1	0	0	0	0	0	0	
Copper carbonate	1	1	0	0	0	0	0	0	0
Copper chloride	2	1	2	0	1	1	2	0	0
Copper cyanide			0						
Copper nitrate	2		0						
Copper oxide	1	1	0		0	0			
Copper sulphate	2	1	0	0	1	1	1	0	0
Copper tetramine compound	2	1	1	0	0	0	0	0	
Corn oil				0					
Cortex cascarae sagradae	1	2	0		0	0	0		
Cotton seed oil	2	1	0	0	0	0	0		
Creosote	1		0	0					
Cresol	0	1	0	0	0	1	0	0	0

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Croton aldehyde	0	1	0	0	0	0	0	0	
Crotonic acid	0	2	0		0	0	0	0	0
Cumaric algehyde			0	0	0	0	0	0	0
Cumarine			0		1	2		0	0
Cumarone, resin	0	0	0	0	0	0	0	0	0
Cumene	0	1	0	0	0	0	0	0	0
Cumohydroperoxide	2	0	0		0	0	0	0	
Cyanacetic acid	2	1	1	0				0	0
Cyanacetic acid ethyl ester	0	1	0	0	0	0	0	0	
Cyan amide		0	0	0	0	0	0		0
Cyanic chloride		2	0		0	0		0	
Cyanogen chloride		1	0	0	0	0	0	0	
Cyanogen, Dicyanogen		1	0	0				0	
Cyclohexane	0	0	0	0	0	0	0	0	0
Cyclohexanol	0	0	0	0	0	0	0	0	0
Cyclohexanol ester	0	1	0	0	0	0	0	0	0
Cyclohexanone				0					
Cyclohexanone	1	1	0	0	0	0	0	0	0
Cyclohexanone oxime		1	0	0				0	0
Cyclohexene	0	1	0	0	0	0	0	0	0
Cyclohexylamine	2	0	0	0	1	1			
Cyclohexylamine carbonate	1	0	0						
Cyclohexylaminelau rate		0	0		0	0	0	0	0
Cyclopentane, Cyclopentadiene	0	0	0		0	0	0	0	0
Cyclopolyolefins			0	0					
p-cymol	0	1	0	0	0	0	0	0	0
Cynacetamide		0	0						
Cystine	1	1	0	0				0	0
DDD		1	0		0	0	0	0	0
DDT, and DFDT	1	1	0		0	1	0	0	0
Dekalin (TM)				0					
Delegol (TM)				0					
Desmodur T (TM)				0					
Desmophen 2000 (TM)				0					
Deuterium oxide	0	0	0		0	0	0		0
Developer (phot.)			0						
Dextrane			0	0		0	0	0	0

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Dextrine	0	0	0	0	0	0	0	0	0
Dextrose	0	1	0	0	0	0	0	0	0
Diacetone alcohol				0					
Dialkyl sulphate	0	1	0	0	0	0	0	0	0
Diazo compounds		1	1	0				0	
Dibenzyle	0	0	0	0	0	0	0	0	0
Dibenzylether				0					
Dibutylmethylenedithioglucolate			0					0	0
Dibuthylphthalate	0	0	0	0	0	0	0	0	0
Dibuthlythiodiglucolate			0					0	0
Dibuthylthiourea		0	0						0
Dichlorbenzene				0					
Dichlorobutylene				0					
Dichloroethane				0	0	0			
Dichloroethylene	0	1	0	0	0	0	0	0	0
Di(p-chlorophenyle) methacarbinole	0	0	0	0	0	0	0	0	0
Dicyclohexyleammoniumnitrite	1	0			0	0			
Diethyl amine	2	1	0	0	1	1		1	0
Diethyl aniline, and Dimenthyl aniline	1	1	0	0	0	0	0	0	0
Diethyiene glycol				0					
Diethyl ether				0					
Diethyl sebacate				0					
Diglycolic acid		1	1	0	1	1	0	0	0
Diglycolic acid dibuthylester	0	1	1	0	0	0	0	0	0
Diisobutyle	0	0	0	0	0	0	0	0	0
Diisopropylectone				0					
Dimenthyl aniline				0					
Dimenthylphenylcarbinole	0	0	0		0	0		0	0
Dimethyl ether	0	0	0	0	0	0	0	0	0
Dimethylformamide				0					
Dioctylphthalate				0					
Dioxane	0	0	0	0	0	0	0	0	0
Dipentene				0					
Diphenyl	0	0	0	0	0	0	0	0	0
Diphenyl amine	1	0	0		0	0	0	0	0
Diphenylene oxide	0	0	0	0	0	0	0	0	0
Diphenylketone	0	0	0	0	0	0	0	0	0
Diphenyl propane	0	0	0	0	0	0	0	0	0

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Dipydoxidiphenyle sulfone		0	0						
DMDT		1	0		0	0	0	0	0
Drilling oil	0	0	0	0	0				
Dye bath			0						
Eggs, egg powder		0	0		0	0		0	
Enamels	0	1	0	0					
Essential oils	1	1	0	0	0	0	0	0	0
Ethane	0	0	0	0	0	0	0	0	0
Ethanol	0	0	0	0	0	0	0	0	0
Ethanolamine		0	0					0	0
Ether				0					
Ethyl acetate	0	0	0	1	1	1	0	0	0
Ethyl acrylate				0					
Ethyl benzene	0	0	0	0	0	0	0	0	0
Ethylbutyrate	0	0	0	0	0	0	0	0	0
Ethyl cellulose			0	0	1	1	0	0	0
Ethyl chloride	0	1	0	0	0	0	0	0	0
Ethyl ether	0	1	0	0	0	0	0	0	0
Ethyl glycol	0	0	0	0	0	0	0	0	0
Ethyl lactate	0	0	0	0	0	0	0	0	0
Ethylene	0	0	0	0	0	0	0	0	0
Ethylene bromide	1	1	0	0	0	0	0	0	0
Ethylene chlorhydrine	0	0	0	0	0	0	0	0	0
Ethylene chloride		0	0	1	0	0	0	0	0
Ethylene cyanhydrine		0	0		0	0	0	0	0
Ethylene diamine		1	0				1	0	
Ethylene dichloride				0					
Ethylene formiate	0	1	0	0	0	0	0	0	0
Ethylene glycol		1	0	0	1	1			
Ethyleneimine		0	0						
Ethylene mercaptane		1	0		1		0		
Ethyl nitrite		0	0						
Ethylene oxide	0	0	0	0	0	0	0	0	0
Ethyl silicate				0					
Ethyl stearate	0	0	0	0	0	0	0	0	0
Ethyl sulphuric acid		2					0	0	
Eukalin (TM)				0					

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Extremely pure water	0	1	0	0	0	0	0	0	0
Fatty acids	1	1	0	0	0	0	0	0	0
Fatty alcohol	0	1	0	0	0	0	0	0	0
Fatty alcohol sulphates	2	1	0	0	0	0	0	0	0
Fats and waxes	1	1	0	0	0	0	0	0	0
Ferric chloride	2	1	2	0	2	2	2	0	0
Ferric potassium cyanide	0	1	1	0	0	0	0	0	
Ferric sulphate	2	1	0	0	2	2	2	0	0
Ferrous chloride	2	1	1	0	1	1	0	0	0
Ferrous potassium cyanide		0	0	0	0	0	0	0	
Ferrous sulphate	2	1	0	0	0	0	0	0	0
Fish oil				0					
Fixing salts			0						
Fluorbenzene				0					
Fluoric acid	1	1	2	0	1	1	1	2	2
Fluorhydrocarbon	0	0	0	2	0	0	0	1	1
Fluorine	1	1	1	1	1	1		2	1
Fluoroboric acid				0					
Fluorocarbon	0	1	1	0	0	0	0		
Fluorocarbonic acids and halogen compounds		1	1	0	1	1	0	1	
Fluorochlorocarbon	0	1	1	0	0	0	0		
Formaldehyde, formaline and metaldehyde	1	1	0	0	0	0	0	0	0
Formamide		1	0	0	1	0	0	0	0
Formic acid	2	2	0	0	1	1	0	0	0
Freon (TM)	0			0					
Fruit			0						
Fruit juices	2		0	0					
Furane				0					
Furfurol	1	1	1	0	1	1	0	0	0
Gallic acid			0						
Gelatine	1	1	0	0	0	0	0	0	0
Generator gas				0					
Genodyn (TM)				0					
Glacial acetic anhydride	2	1	0	0					

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Glacial acetobromic acid				0					
Gluconic acid	0	1	0	0	0	0	0	0	0
Glucose				0	0	0			
Glue	1	1	0	0					
Glutamic acid	2	1	0	0	1	0		0	0
Glycerine	1	1	0	0	0	0	0	0	0
Glycol acid	1	1	1	0	1	1	0	0	0
Glycol, Diethyleneglycol	1	1	0	0	0	0	0	0	0
Glycoxy acid		2	0	0	1	1	0	0	
Grease				0					
Halowaxoil (TM)				0					
Hemp and jute	1	1	0	0	0	0	0	0	
Heptane	0	0	1	0	0	0	1	0	0
Hexachlorobutadiene				0					
Hexachloroethane	1	1	1	0	1	1	1	0	
Hexaldehyde				0					
Hexamethylenetetramine	1	1	0	0	1	2	0	0	0
Hexane				0					
Humic acid	0	1	0	0	0	0	0	0	0
Hydraxylamine sulphate				0					
Hydrazine		1	1		2	2	1		
Hydrazine sulphate			1						
Hydrobromic acid				0	2	2	1	0	
Hydrochloric acid	1	1	1	0	0	0	0	0	1
Hydrochloric acid	2	1	1	0	1	1	0	0	1
Hydrocyanic acid	2	1	0	0	2	2	0	0	0
Hydrocyanic acid	2	1	0	0	2	2	0	0	0
Hydrogen	0	1	1	0					
Hydrogen bromide		1	2	0	1		1	0	
Hydrogen gas				0					
Hydrogen iodide, iodic acid	1	1	1	0	1	1	0	0	0
Hydrogen peroxide	1	1	0	0	1	2	2	0	2
Hydrogen sulphide	1	1	0	0	1	0	0	0	0
Hydroquinone		1	0	0	0	0	0	0	0
Hypochloric acid	2	2	2	0				0	
Impregnating oils	0	1	0	0	0	0	0	0	0

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta- lum	Tita- nium
Indol	0	0	0	0	0	0	0	0	0
Ink (Ferrogallic)		1		0					
Iodine	2	1	1	0	1	1	1	0	1
Iodoform		1	1		0	0	0	0	0
Iron nitrate	2	2	0	0	2	2		0	
Iron phosphate			0						
Isatine, derivates	0	1	0	0	0	0	0	0	0
Isobutyl alcohol				0					
Isopropyl acetate				0					
Isopropyl alcohol				0					
Isopropyl chloride				0					
Isopropyl ether				0					
Kerosene				0					
Lactame				0					
Lactic acid	1	1	1	0	2	2	1	0	0
Lactose		1	0	0	0	0	0	0	0
Lead acetate	1	2	0	0	1	1	0		
Lead acetate			0						
Lead acetate			0						
Lead arseniate	0		0	0	0	0	0	0	
Lead baths (electrolyt.)		1		0		0			
Lead bromide		2	1				1		
Lead carbonate	0	1	0	0	0	0	0	0	
Lead chloride		1	0	0		0	0	0	
Lead chromate	0	0	0	0	0	0	0	0	
Lead dioxide	0	0	0	0	0	0	0	1	
Lead (molten)	2	1	1	2	2	2			
Lead nitrate		1	0	0	0	0	0	0	
Lead nitride	0		0	0	0	0	0		
Lead oxide		1	1				1	1	
Lead rhodanide	0	2		0	0	0	0	0	
Lead sulphate	0	1	0	0	0	0	0		
Lead sulphide	2	1	1		2				
Lead tetra-acetate			0				0		
Lead trinitroresorcinate			0	0		0	0		
Lecithine		1	0	0	0	0	0	0	0

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Levulic acid		2	1	0	1	1	0	0	
Lignite tar	1	1	0		0	0	0		
Lime milk			0	0					
Limonene	1	1	0	0	0	0	0	0	0
Linseed oil	1		0	0	0	0			
Liqueur			0						
Lithium bromide				0					
Lithium carbonate		1	0	0	0	0	0		
Lithium chloride	1	1	1	0	1	1	0	0	1
Lithium hydride		1	0	1	1				
Lithium hydroxide	2	1	0	1	1	0			
Lithium (molten)	2	1	1	0	1	2		0	
Lithium sulphate	0	1	0	0	0	0	0	0	0
Litopone	0	1	0	0	0				
Lysoform			0						
Lysol			0						
Magnesium bisulphite		2	1	0	1	1	0	0	0
Magnesium carbonate	0	1	0	0	0	0	0	0	0
Magnesium chloride	2	1	1	0	1	0	0	0	0
Magnesium fluoride	1	1	1	0	1	1		1	
Magnesium hydroxide				0	0	0			
Magnesium (molten)	2	1	1	0					
Magnesium nitrate	1	1	0	0	2	2	2	0	0
Magnesium oxide	1	0	0	0	0	0	0	0	1
Magnesium oxychloride	1	1	1	0	0	0	0	0	0
Magnesium silicofluoride		1	0	0		1		2	
Magnesium sulphite	0	1	0	0	0	0	0	0	0
Magnesium sulphate	1	1	0		0	0	0	0	0
Maleic acid	1	1	0	0	0	0	0	0	0
Maleic acid, anhydride	2	1	0	0	0	0	0	0	0
Maleic anhydride				0					
Malic acid	0	2	0	0	0	0	0	0	0
Malonic acid	1	1	0	0	1	1	1	0	1
Malt	0	1	0	0	0	0	0		0
Maltose	0	0	0	0	0	0	0	0	0
Manganese dioxide		1	0	0	1	1		1	0
Manganese sulphate	1	1	0	0	0	0	0	0	0

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Manganic chloride		1	1	0	1	1		0	0
Manganous chloride			0						
Meat			0						
Menthol	1	1	0		0	0	0	0	0
Mercaptane	1	2	0	0	1	1	0	0	0
Mercury	2	1	0	0	0	2	1	0	1
Mercury chloride	2	2	1	0	2	2			
Mercury cyanide	2	2	0		2	2			
Mercury nitrate	2	2	0		2	2			
Mercury salts	2	2						0	
Mersolates		1	1	0	0	0	0	2	
Mesamoll (TM)				0					
Methane	0	1	1	0	1	0	0	1	1
Methane				0					
Methane chlorobromide		0	0	0	0	0	0	0	
Methanol	1	1	1	0	0	0	0	1	1
Methyl acetate	1	1	1	1	1	0	0	0	0
Methyl acrylate				0					
Methyl alcohol	0		0	0	0	0			
Methyl aldehyde	1	1	0	0					
Methyl amine	2	1	1	0	1	2			0
Methyl bromide	0	1	1	0	0	0	0	0	
Methyl chloride	1	1	1	0	0	0	0	0	0
Methyl chloride				0					
Methyl ethyl cetone	0	1	0	0	0	0	0	0	0
Methyl formiate	0	0	0	0	0	0	0		0
Methyl isobutylcetone				0					
Methyl methacrylate				0					
Methyl salicylate				0					
Methylene chloride	1	1	1	0	0	0	0	0	0
Milk	1		0	0	1	1			
Molasses	1	1	0	0	0	0	0	0	0
Monobrombenzene				0					
Morphine		2	0	0				0	0
Morpholine	0	0	0	0	0	0	0	0	
Mortar	1	1	1	0	0	0	0	0	
Mustard		2	0						
Naphtaline	0	0	0	0	0	0	0	0	0

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta- lum	Tita- nium
Naphtaline sulfonic acid		1	1	0	1	1	1	0	1
Naphtenic acid	1	1	0	0	0	0	0	0	0
Naphtochinoline		0	0	0				0	0
Naphtol		1	0	0	0	0	0	0	0
Naphtolen 2 D (TM)				0					
Naphtylamine	1	0	0	0				0	0
Naphtylaminesulfonic acid	1	1	0	0				0	
Nibren wax				0					
Nickel chloride	2		1	0	1	0	0	0	0
Nickel nitrate			0		1	1	1	0	0
Nickel salts		2	0	0					
Nickel sulphate	1		0	0	1	1	0	0	0
Nitric acid	2	1	0	0	2	2	2	0	1
Nitric acid, strong conc.	2		1						
Nitrobenzene		0	0	0	0	0	0	0	0
Nitrogen	0	1	0	0	0	0	0	0	0
Nitrous acid			1						
Nitrous oxide gas				0					
Novocaine			0						
Oak extract	1	1	0	0	0	0	0	0	0
Oleic acid	1	1	0	0	1	1			
Olein				0					
Oleum				0	1	1	1	1	2
Olive oil				0					
Oxalic acid	2		1		2	1	0	0	1
Oxygen	0	1	0	0					
Oysters		2	0			0			
Ozone		1	0	0	1	1		0	0
Palm oil acid		0	0	0	0	0			
Paraffine	0	0	0	0	0	0			
Peanut butter		0	0		0	0	0		
Pentachlorodiphenyle				0					
Pentane				0					
Perchlorethylene	1	1	0	0	0	0	0	0	0
Perchloric acid	2	2	2	0					
Petrol ether			0						

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Petrol, natural gas	1	1	0	0	1	1	0	0	
Petroleum	1	0	0	0					
Phenol	1		0	0	1	1	0	0	0
Phenyl benzene				0					
Phenyl ether				0					
Phenyl hydrazine				0					
Phosphoric acid	2	1	0	0	1	1	1	0	1
Phosphoric acid anhydride			0						
Phosphorous chloride				0					
Phtalic acid	0	1	0	0	1	1	1	0	0
Pickling liquid			0						
Picric acid	2	1	0	0	2	2			
Pine oil				0					
Piperidine				0					
Polyglycol				0					
Potash lye	1	1	1	0	0	0	1	1	1
Potassium			0						
Potassium acetate	0	0	0	0	0	0	0	0	0
Potassium bisulphite	0	1	0	0	1	1		0	
Potassium bisulphate			1	0					
Potassium bitartrate			1						
Potassium bromide	0	1	1	0	0	0	0	0	0
Potassium carbonate	1	0	0	0	0	0			
Potassium chlorate		1	0	0	0	0		0	0
Potassium chloride	2	1	1	0	0	0	0	0	1
Potassium chromesulphate	1	2	1	0	1	1	0	0	0
Potassium cyanate			0						
Potassium cyanate			0						
Potassium cyanide	2	1	0	0	1	0	1	0	2
Potassium dichromate	0	1	0	0	0	0		0	0
Potassium difluoride			0						
Potassium fluoride	0	0	0	0	0	0	0		
Potassium hydrogen fluoride	1	1	0	0	0	0	0		2
Potassium hydroxide	1	1	1	0	0	0	1	1	1
Potassium hydroxide	1	1	1	0	0	0	1	1	1
Potassium hypochlorite		1	1	0	1	1		1	0
Potassium iodate		1	0	0				0	0
Potassium iodide		1	1	0	0		0	0	0

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Potassium monochromate	0	1	0	0	0	0		0	0
Potassium nitrate	1	1	1	0	0	0		0	0
Potassium nitrite	1	1	1	0	0	0		1	1
Potassium oxalate			0						
Potassium perchlorate		1	0	0	0	0		1	1
Potassium permanganate	1	1	0	0	1	1		1	
Potassium peroxide	2	1	1	0	1	0	1	2	
Potassium persulphate				0	2	0	0	0	
Potassium phosphate	1	1	1	0	0	0	1	0	1
Potassium rhodanide		1	0	0	0	0	0	0	
Potassium silicate	0	1	0	0	0	0	0	1	0
Potassium sulphate	0	1	0	0	0	0	0	0	0
Potassium sulphide, sulphite	1	1	0	0	1	1	1	0	
Propane	0	0	0	0	0	0			
Propane chlorobromide	1	1	0		0	0	0	0	
Propylene chlorobromide	1	1	0		1	1	0	0	
Propylene oxide		1	0	0					
Protein solutions	1	1	0	0	0	0	0	0	0
Pydraul (TM)				0					
Pyridine	1	0	0	0	0	0	0	0	0
Pyrocatechin		1	0		0	0	0	0	0
Pyrogallol			0						
Pyrrole				0					
Pyruvic acid		2	0		0	0	0	0	
Quinic acid	0	2	0	0	0	0	0	0	0
Quinine	0	1	0	0	0	0	0	0	0
Quinine disulphate	0	2	0	0			0		
Quinine hydrochloride		2	2				0	0	
Quinine monosulphate	0	2	0	0	0	0	0	0	
Quinine sulphate			0						
Quinine tartrate	0	1	0	0	0	0	0	0	
Quinizarine		0	0		0	0	0	0	0
Quinoline	0	1	0	0	0	0	0		
Rape oil				0					
Rhodinol	0	1	0	0					
Sagrotan (TM)				0					

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Salicylic acid	0	2		0	0	0			
Sea water	1	2	0	0	0	0	2	0	0
Siliccofluorhydric acid	2	2	1	0	1	2	1	2	2
Silver bromide	2		0						
Silver nitrate		2	0	0	2	2		0	
Skydrol (TM)				0					
Sodium	1	1	1	1	1	1	1	0	1
Sodium acetate	1	1	0	0	0	0	0	0	0
Sodium aluminate	0	1	0	0	0	0			
Sodium aluminium fluoride		0	0	0	0	0	0		2
Sodium aluminium sulphate	1	2	1	0	1	1	0	0	
Sodium arseniate, arsenite	0	0	0	0	0	0	0		
Sodium benzoate	0	0	0	0	0	0	0	0	0
Sodium bicarbonate	1	1	0	0	0	0	1		0
Sodium bisulphite	2	2	0	0	1	0		0	0
Sodium bisulphate	2	1	1	0	1	1	1	0	1
Sodium borate	1	1	1	0	1	0	0	1	0
Sodium boron hydride			0						
Sodium bromate		1	0	0				0	
Sodium bromide		1	1	0	0	0	0	0	0
Sodium bromite			0	0	0				
Sodium carbonate	1	1	0	0	1	1	0	1	1
Sodium carbonate			1	0	0	1			
Sodium chlorate		1	0	0	1	1		0	0
Sodium chloride				0					
Sodium chloride	1	1	1	0	1	1	0	0	1
Sodium chlorite	1	2	1	0	1	1	2	1	0
Sodium chloroacetate	1	1	0	0	0	0	0	0	
Sodium chromate	0	1	1	0	0	0	0	0	0
Sodium citrate			0						
Sodium citrate		1	0	0	1		2	0	
Sodium cyanamide	1	1	0			0			
Sodium cyanate	2	1	0	0	1				0
Sodium cyanide				0	1	1		1	1
Sodium dichromate				0					
Sodium dichromate	2				0	0	2	1	1
Sodium diphenylsulfonate		1	0	0	0	0			
Sodium dithionite	2	2	0	0	0	0	0	0	

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Sodium duodecylebenzenesulfonate	1	1	0	0	0	0	0		
Sodium ethylate		0	0	0	0	0			
Sodium ethylene diamine tetraacetate		0	0	0	0	0	0		
Sodium fluoroacetate		0	0	0	0	0			
Sodium fluorophosphate	0	0	0	0					
Sodium formiate	0	0	0	0	0	0	0	0	
Sodium glutamate	2	1	0	0	0	0	0		
Sodium hydrochloride	2		1	0	1	1	1	1	1
Sodium hydrogen sulphide	2	1	0	0			0		
Sodium hydroxide	2		1	0	1	1	1	1	1
Sodium hydroxide	2		1	0	1	1	1	1	1
Sodium hypochlorite	2	1	1	0	1	1		0	0
Sodium hypochlorite	2	1	1	0	1	1		0	0
Sodium iodide		1	1	0	1	0		0	0
Sodium nitrate	1		0	0	1	1	1	0	0
Sodium perborate			0	0	0				
Sodium perchlorate			0		0	0		1	1
Sodium peroxide	2		0		1	0	0		2
Sodium phosphate	1		0	0	1	1	1	0	
Sodium and potassium alloys	1	1	1	0	0	1	0	0	1
Sodium pyrosulphite			0	0		0			
Sodium salicylate			0	0	0	0	0	0	
Sodium silicate	1		0	0	0	0	0	0	
Sodium silicate	1		0	0	0	0	0	0	
Sodium sulphite	2		0	0	0	0	0	0	0
Sodium sulphate	1		0	0	1	1	1	0	1
Sodium sulphide	1		1	0	1	1	1	1	0
Sodium thiosulphate	1		0	0	0	0	0		0
Soft soap, suds	1	0	0	0					
Solder flux	1	1	1	0	0	1			
Spinning bath			1	0					
Stannous chloride	2	2	1	0				0	
Stearic acid	1	2	0	0	0	0			
Styrene				0					
Succinic acid	0	1	0	0	0	0	0	0	0
Sugar beet juice					0				
Sugar solution	1	1	0		0	1			
Sulfite lye	2	2	0	0	2	2	0	0	0

Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta-lum	Tita-nium
Sulphur	1	1	0	0	1	1	1	0	0
Sulphur, boiling	1	1	1						
Sulphur chloride (dry)	0								
Sulphur dioxide	1	1	0	0	1	0	1	0	1
Sulphuric acid	2	2	1	0	1	1	1	0	1
Sulphuric anhydride		2		0					
Sulphurous acid	2	1	0	0					
Sulphurous chloride	1	0	0	0	0	0		0	2
Tannin	1		0	0					
Tannin	1	1	0	0	1	1			
Tar, pure	1	2	0	0					
Tartaric acid	2		1	0	1	1			
Tetrachloroethane	1	1	1	0					
Tetrachloroethylene				0					
Tetrahydrofurane				0					
Tetraline				0					
Tin chloride		2	1	0	1	1	0	0	0
Tin chloride solution				0					
Tin, molten, 300 °C	2	2	0						
Tin, molten, 500 °C	2	2	2						
Titanium tetrachloride				0					
Toluene	0	1	0	0	0	0			
Transformer oil				0					
Tributoxyethylphosphate				0					
Tributyl phosphate				0					
Trichloracetic acid			2	0					
Trichloroethane				0					
Trichloroethylene	1	1	0	0	0	0	0		1
Trichloroethylphosphate				0					
Tricresylphosphate				0	0		0		
Triethanolamine				0					
Triethyl glycol				0					
Trisodiumphosphate			0						
Turpentine	0	1	0	0	0	0			
Uranium fluorides					0	0	1	2	
Urea	1	1	0	0	1	1	0	0	0

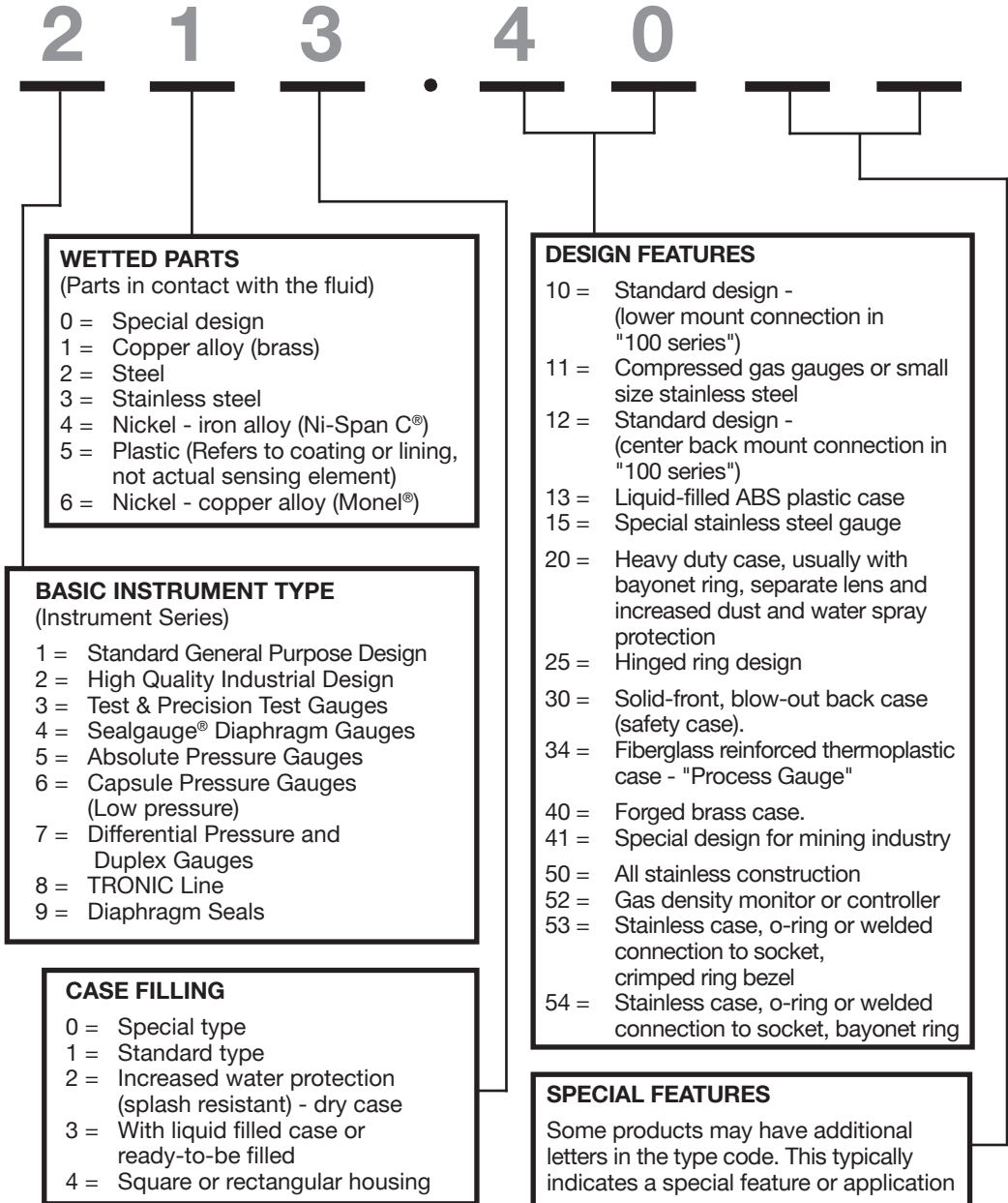| Aggressive substances	Cu alloy	Steel	316 SS	PTFE	Nickel	Monel	Hastelloy	Tanta- lum	Tita- nium
Urea resins	0	1	0		0	0	0		
Uric acid		2	0	0	0	0	0	0	
Urine			0						
Varnish	0	1	0	0	0	0	0	0	
Vaseline			0						
Vegetables			0						
Vegetal tar, charcoal	0	1	0	0	0	0	0	0	
Vinegar			0	0					
Vinyl acetate			0	0					
Vinyl acetate acetic acid				0					
Vinyl chloride				0	1	1	1	0	
Viscose				0					
Wash oil		1	0			0	0		
Water	1	2	0	0	0	0			
Wine	1	2	0	0					
White lye				0					
Wood's alloy				0					
Xylamone			0						
Xylene			0	0	1	1			
Xylene-dimethylformamide				0					
Yeast	1	1	0	0	0	0	0	0	0
Zinc chloride	2	1	1	0	1	0	1	0	1
Zinc, molten 300 °C	2	2	0						
Zinc, molten 500 °C	2	2	2						
Zinc salts				0					
Zinc sulphate	2	2	0	0	1	1			

Legend

0 = good corrosion resistance, attack: none or very slight.
1 = is being attacked, may be used in certain cases.
2 = no corrosion resistance, strong attack in a short time.

If no rating is given, we do not have information on the resistance properties.

WIKA Type Numbers

The following is a guide to the WIKA model numbering system.

2   1   3 · 4   0

WETTED PARTS
(Parts in contact with the fluid)

0 = Special design
1 = Copper alloy (brass)
2 = Steel
3 = Stainless steel
4 = Nickel - iron alloy (Ni-Span C®)
5 = Plastic (Refers to coating or lining, not actual sensing element)
6 = Nickel - copper alloy (Monel®)

BASIC INSTRUMENT TYPE
(Instrument Series)

1 = Standard General Purpose Design
2 = High Quality Industrial Design
3 = Test & Precision Test Gauges
4 = Sealgauge® Diaphragm Gauges
5 = Absolute Pressure Gauges
6 = Capsule Pressure Gauges (Low pressure)
7 = Differential Pressure and Duplex Gauges
8 = TRONIC Line
9 = Diaphragm Seals

CASE FILLING

0 = Special type
1 = Standard type
2 = Increased water protection (splash resistant) - dry case
3 = With liquid filled case or ready-to-be filled
4 = Square or rectangular housing

DESIGN FEATURES

10 = Standard design - (lower mount connection in "100 series")
11 = Compressed gas gauges or small size stainless steel
12 = Standard design - (center back mount connection in "100 series")
13 = Liquid-filled ABS plastic case
15 = Special stainless steel gauge
20 = Heavy duty case, usually with bayonet ring, separate lens and increased dust and water spray protection
25 = Hinged ring design
30 = Solid-front, blow-out back case (safety case).
34 = Fiberglass reinforced thermoplastic case - "Process Gauge"
40 = Forged brass case.
41 = Special design for mining industry
50 = All stainless construction
52 = Gas density monitor or controller
53 = Stainless case, o-ring or welded connection to socket, crimped ring bezel
54 = Stainless case, o-ring or welded connection to socket, bayonet ring

SPECIAL FEATURES

Some products may have additional letters in the type code. This typically indicates a special feature or application

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4.3 Legend of symbols used

Section 1: Pressure measurement

Symbol	Designation	Notes
A	area	
C	electrical capacitance	
C_P	measuring capacitance	
C_R	reference capacitance	
E	modulus of elasticity	
EP	end point of a Bourdon tube	
F	force	
E_{indic}	indicating error	
F_N	normal force, i.e. a force acting perpendicular to its point of application	
E_{rel}	relative indicating error	
G	weight	
J	moment of plane area of a tube cross-section	
M	torque; the restoring torque of a Bourdon tube	
R	radius of the centre of mass	only: *(1-15)*
R	free radius of a fitted diaphragm	only: *(1-36, 1-37)*
R	electrical resistance, effective resistance	
ΔR	electrical resistance differential	
R_A	load impedance	
R(p)	pressure-dependent resistors	
S	cross-sectional face of an electrical conductor	
fsd	full scale deflection	
T	temperature	
U_S	supply voltage	
U_{Smin}	minimum supply voltage	
U_S	signal voltage	
U_O	offset voltage	
V	volume, capacity	
ΔV	change of volume of a bourdon tube, or displacement volume of a diaphragm under pressure	
V_N	capacity of a bourdon tube at nominal pressure	
V_O	capacity of a bourdon tube at $p_e = 0$	
W	energy	
W_{lig}	energy of a pressurized liquid	
W_{gas}	energy of a pressurized gas	
X_i	indicated measured value (actual indication)	
X_c	correct measured value (desired indication)	
a	large semi-axis of the cross-section of a bourdon tube	
b	small semi-axis of the cross-section of a bourdon tube	
c	part of the corrugated profile of a diaphragm	
d	wall thickness of a bourdon tube or diaphragm	
$f_{(N, H)}$	coefficients of the change of curvature of low-pressure or high-pressure spring elements	
e	part of the corrugated profile of a diaphragm	

Symbol	Designation	Notes
$f_{(N', H')}$	coefficients of the bending stress of low-pressure or high-pressure spring elements	
f_M	coefficient of spring rigidity	
$f(q,p)$	size- and pressure-dependent auxiliary function	
g	factor of acceleration due to gravity	
$g(...)$	size- and pressure-dependent auxiliary function	
h	height of diaphragm shaping	only: *(Fig. 1.71; 1.72)*
Δh	height differential of a liquid column	
k	degree of coupling	only: *(1-29)*
k	constant proportionality factor	
k	k factor of strain gauges	only: *(1-70)*
k_{red}	reduction coefficient for calculating corrugated diaphragms	
k'	length of distance from the polar point to the end point of a Bourdon tube	
l	length of a resistance wire	
l	length of a diaphragm's corrugation	only: *(1-38)*
l	plate spacing	only: *(1-27)*
m	mass, weight as a weighing result	
n	number, general figure	
p	pressure	
p_{abs}	absolute pressure	
p_{amb}	ambient atmospheric pressure	
p_e	positive pressure, atmospheric pressure difference	
Δp	difference between two pressures $p_1 - p_2$	
p_N	nominal pressure of a device (fsd)	
r	mean radius of the separating liquid	only: *(1-15)*
r_O	radius of curvature of an unloaded Bourdon tube	
q_{leak}	leakage rate	
s	spring path	
t	time, time interval, duration	
v_{med}	mean molecular velocity	
α	angle of inclination, angle of rotation	
β	angle between a segment's centre of rotation, control point and end point EP	
ε	elongation, relative change of length	
ε_0	electrical field constant, dielectric constant of vacuum	
ε_r	permittivity constant (dielectric constant)	
κ	compressibility of a liquid	
λ	characteristic value of a Bourdon tube	
ρ	specific effective electrical resistance	
$\Delta \rho$	change of specific electrical resistance	
ρ_F	density of the filling liquid	
ρ_L	density of air	
μ	Poisson's ratio	
ρ_m	density, volume-related mass	
σ_s	tensile yield strength	
σ_{bmax}	maximum bending stress, ultimate strength	
ψ_0	coil angle of an unloaded Bourdon tube	

4 Appendix and tables

Symbol	Designation	Notes
ψ_1	coil angle of a loaded Bourdon tube	
ω	relative change of curvature	

Section 2: Thermometry

Symbol	Designation	Notes
A	cross-sectional area of a rod	
A	area of a protective tube exposed to flow	only: (2-34)
A	thermometer surface	only: (2-56)
A	bend of a bimetallic strip	only: (2-83)
A	interface between two materials	only: (2-52)
A_r	path in distance r of a bimetallic helix	
A_S	annulus area of a cylindrical protective tube	
A_u	partial suppressed bend of a bimetallic strip	
B	form- and material-dependent constant of an NTC resistor	
C	capacitance	
C	constant	only: (2-27)
C	constant referred to as the volumetric absorption capacity dependent on the thermometer type	only: (2-95)
C(T)	temperature-dependent sound velocity in gas	
C_0	sound velocity in gas at reference temperature T_0	
C_t	correction factor for water temperature	
C_β	correction factor for angle of incident flow	
C_{be}	correction factor for coating and/or contamination of a protective tube	
C_S	technical radiation constant	
C_{th}	mean specific thermal capacity of a thermometer	only: (2-73)
E	electrical field	
E	modulus of elasticity of a material	only: (2-36)
E	sensitivity of a liquid-in-glass thermometer	only: (2-82)
E_W	self-heating error of a thermometer in water	
E_L	self-heating error of a thermometer in air	
E_X	self-heating error of a thermometer in the measured medium X	
F	setting force of a bimetallic strip	
F(p)	complex frequency response of a delay element	
F_U	setting force with partially suppressed bending of a bimetallic strip	
$F_{permiss}$	maximum permissible force	
F_L	relative measurement error in air according to VDI/VDE 3522	
F_a	axial compressive force of a protective tube in a flowing medium	
F_0	frequency at reference temperature T_0	
F_X	relative installation error of a thermometer in the measured medium X	
G_{th}	coefficient of thermal conductivity of an NTC resistor	

Symbol	Designation	Notes
I_m	measurement current	
J	axial geometrical moment of inertia	
K_T	thermometer characteristic	
L_λ	spectral density of radiation of a black body with temperature T_{90}	
L_ϑ	lengths of a rod at temperature ϑ	
L_0	initial length of a rod at temperature ϑ_0	
dL	differential change of length of a rod (as a function of the differential change of temperature)	
M	torque	
M_U	torque of a bimetal with totally suppressed movement of rotation	
M_1	torque at the clamping point of a protective tube, resulting from dynamic pressure force	
M_2	bending moment at the clamping point of a protective tube, resulting from axial compressive force	
P_V	power loss of a thermistor	
P_Q	transported thermal power	
P_{st}	thermal energy transmitted by radiation	
P_1	electrical output with measuring current I_1	
P_2	electrical output with measuring current I_2	
Q	amount of heat	
Q	dynamic pressure force	only: *(2-34)*
R	resistance	
R	universal gas constant	only: *(2-97)*
$R(T_{90})$	resistance of a platinum resistance thermometer at temperature T_{90}	
$R_{(273,16)}$	resistance of a platinum resistance thermometer at triple point water temperature	
$R(t)$	temperature-dependent resistance of a metal resistance (thermometer) sensor at temperature t	
R_0	resistance value of a metal resistance thermometer at reference temperature t_0	
R_{KL}	temperature-dependent total resistance of a PTC resistor	only: *(Fig. 2.9)*
R_{grain}	grain resistance of a PTC resistor	
$R_{grain\ boundary\ layers}$	temperature-dependent resistance of the grain boundary layers of a PTC resistor	
R_{min}	minimum resistance of a PTC resistor	only: *(Fig. 2.10)*
R_b	reference resistance of a PTC resistor	
R_p	resistance of a PTC resistor in the steep zone	
R_T	resistance of an NTC resistor at temperature T	
R_{T0}	resistance of an NTC resistor at reference temperature T_0	
R_1	resistance value of an NTC resistor at temperature value T_1	
$R_2{}^0$	resistance value of an NTC resistor at temperature value T_2	
R_e	Reynolds number	
R_S	sensor resistance	
R_{isol}	insulation resistance of a resistance thermometer	

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Symbol	Designation	Notes
S	thermoelectric power	
S_A	thermoelectric power of a metal conductor A	
S_B	thermoelectric power of a metal conductor B	
St	Strouhal number	
T	temperature	
T_C	Curie temperature	
T_{tr}	temperature of the triple point of water	
T_K	temperature in Kelvin	
T_R	temperature in Rankine degrees	
T_{90}	temperature in Kelvin measured according to ITS 90	
T_1	temperature value	
T_2	temperature value	
T_p	temperature above the reference point of a PTC resistor	only: *(Fig. 2.10)*
T_0	reference temperature (of an NTC resistor)	
T_{Rmin}	temperature at which the PTC resistor displays minimum resistance	only: *(Fig. 2.10)*
T_t	surface temperature of a thermometer	
T_w	surface temperature of a measured medium vessel	
T_x	temperature of the measured medium X	
T_{thx}	sensor temperature in the measured medium X	
T_W	wall or flange temperature of a thermometer	
$T_{th}(t)$	thermometer temperature at time t	
T_m	measured medium temperature	
U	voltage	
U_D	conducting voltage of a diode	
$U_C(t)$	capacitor voltage at time t	
U_0	process voltage at an R-C element input	
U_S	self-heating error of a resistance thermometer	
U_{th}	thermoelectric voltage	
$\dfrac{dU_{th}}{dt_{ref}}$	gradient of thermoelement curve at reference point temperature	
$\dfrac{dU_{th}}{dt_{mess}}$	gradient of thermoelement curve at measuring point temperature	
V	volume	
V_ϑ	volume of a liquid at temperature ϑ	
V_0	volume of a liquid at temperature ϑ_0	
V_m	volume related to substance quantity	
V_n	effective spring volume of a liquid spring thermometer	
V_T	thermometer transfer behaviour parameter	
V_{TE}	thermometer self-heating parameter	
V_F	volume of the thermometer bulb of a liquid spring thermometer	
V_K	volume of long distance of a liquid spring thermometer	
$V_{T\eta}$	thermometer transfer time parameter	
W	energy	
W	resistance moment of a protective tube at the clamping point	only: *(2-39)*
$W(T_{90})$	resistance ratio of a platinum resistance thermometer	
W_{max}	maximum energy capacity of a bimetallic helix	

Symbol	Designation	Notes
Z_n	angular frequency coefficient of a tube	
a	specific thermal bend	
a	material-specific temperature coefficient of the 1st order	only: *(2-19)*
a	type-specific constant of a thermolinear thermistor	only: *(2-26)*
a,b	specific gas constants	only: *(2-97)*
a_i	quartz-related temperature coefficients	
a_F	conversion factor for liquids in relation to water	
a_G	temperature factor for heat radiation	
b	width of a bimetallic strip	
b	material-specific temperature coefficient of the 2nd order	only: *(2-19)*
b	type-specific constant of a thermolinear thermistor	only: *(2-26)*
c	material-specific temperature coefficient of the 3rd order	
c_2	2nd Planck's constant with a value $C_2 = 0.014388$ m · k specified in ITS 90	
c_{th}	coefficient of internal heat transfer of a thermometer	
d_a	outside diameter of a protective tube	
d_i	inside diameter of a protective tube	
f	bending of a protective tube exposed to flow	
f	indicating error of a liquid spring thermometer	only: *(2-96)*
f_W	frequency of vortex of a protective tube exposed to transverse flow	
f_r	resonance frequency of a protective tube	
f_g	limiting frequency	
f(T)	temperature-dependent output frequency of an oscillating circuit	
h	Planck's constant	
k	correction factor	
k	Bolzmann constant	only: *(2-30)*
k_e	material-dependent constant	
k_f	thread correction of a liquid-in-glass thermometer	
l	overall length of a protective tube	
l	length of the long-distance capillary line of a liquid spring thermometer	only: *(2-96)*
l	length of thread section	only: *(2-82)*
n	gas quantity in number of moles	
p	pressure	
Δp	change in internal pressure of a gas	
q	inside cross-section of the long-distance capillary line of a liquid spring thermometer	
r_a	outside radius of a protective tube	
r_i	inside radius of a protective tube	
r_1	distance from the centre of a bimetallic helix	
s	thickness of a bimetallic strip	
t	temperature in degrees Celsius	
t	temperature at a thermometer measuring point	only: *(2-100)*
Δt	temperature difference	
Δt	indicating error of a resistance thermometer	only: *(2-99)*

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Symbol	Designation	Notes
Δt	deviation of reference point temperature from 0°C	only: *(2-100)*
Δt	change of ambient temperature in relation to the reference temperature	only: *(2-96)*
Δt_e	excess temperature	
t_c	temperature in degrees Celsius	
t_f	thread temperature of a liquid-in-glass thermometer	
t_F	temperature in degrees Fahrenheit	
t_{fs}	rated thread temperature of a liquid-in-glass thermometer	
t_X	transfer time of a thermometer in the measured medium X	
t_L	transfer time of a thermometer in air	
t_W	transfer time of a thermometer in water	
t_0	starting time	
t_{10}	10% response time of a thermometer	
t_{50}	50% response time of a thermometer	
t_{90}	90% response time of a thermometer	
t_{90}	temperature in degrees Celsius measured according to ITS 90	only: *(p. 143)*
$\overline{u}^2$	mean square noise voltage	
v	flow velocity of the medium	
ϑ	temperature in degrees Celsius	
ϑ_0	reference temperature	
$d\vartheta$	differential temperature change in degrees Celsius	
α	linear temperature coefficient	
α	angle of rotation of a bimetallic helix	only: *(2-87)*
α	linear expansion coefficient of the thermometer vessel	only: *(2-95)*
α_K	specific heat transfer coefficient at interfaces	
α_W	specific heat transfer coefficient in water	
α_{nw}	specific heat transfer coefficient in water at 20°C	
α_L	specific heat transfer coefficient in air	
α_{nL}	specific heat transfer coefficient in air at 20°C	
α_F	specific heat transfer coefficient for liquids	
α_G	specific heat transfer coefficient for gases	
α_{St}	heat radiation transfer coefficient	
α_{th}	specific overall heat transfer coefficient of a thermometer	
α_{xeff}	effective heat transfer coefficient of a thermometer in the measured medium X	
α_{thx}	heat transfer coefficient of a thermometer in the measured medium X	
α_{thm}	heat transfer coefficient of a thermometer in the measured medium M	
α_{thL}	heat transfer coefficient of a thermometer in air according to VDI/VDE 3522	
α_{meff}	effective heat transfer coefficient of a thermometer in the measured medium M	
α_{Leff}	effective heat transfer coefficient of a thermometer in air according to VDI/VDE 3522	
β	cubic temperature coefficient	
$\delta_C\,(t-t_0)$	dynamic relative response error (R-C element)	

Symbol	Designation	Notes
$\delta(t)$	dynamic relative response error of a thermometer	
ε	degree of emission of a thermometer surface	
χ	compressibility	
γ	relative expansion coefficient	
γ	volumetric expansion coefficient	only: *(2-95)*
$\eta_C(t\text{-}t_0)$	relative response function of an RC element	
$\eta(t)$	relative response function of a thermometer	
λ	wavelength referred to vacuum	only: *(2-14)*
λ	kinematic viscosity	
λ	specific thermal conductance of a material	
ν	viscosity of a medium	
ρ	density of air	
ρ	density of flowing medium	
σ_K	tangential stress for cylinders under outside pressure	
σ_b	bending stress resulting at the clamping point of protective tube	
σ_V	reference stress of a protective tube at the clamping point	
$\sigma_{permiss}$	maximum permissible stress of a material	
τ	time constant of a thermometer	
τ_C	time constant of a RC element	
τ_1, τ_2	delay time constant of a thermometer	
τ_V	time constant of a thermometer	
ω	angular frequency	
ω	resulting angular frequency of a protective tube	only *(2-49)*
ω_R	angular frequency of a tube	
ω_B	angular frequency of a mass-less bar with point mass	
ξ	protective tube specific resistance number	
$\Psi(w)$	phase displacement	

Section 3: Process engineering requirements for the measurement of pressure and temperature

Symbol	Designation	Notes
A_0	piston area	
C	capacitance	
I	electricity	
I_2	discharge current during the deintegration phase	
N_1	number of logic "ones"	
N_0	number of logic "zeros"	
R	resistance	

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Symbol	Designation	Notes
R_i	internal impedance	
R_L	load impedance	
S_1	voltage rise during the integration phase	
S_2	voltage rise during the deintegration phase	
S_{vj}	standard deviation	
S_{xj}^2	empirical variance estimate	
S_y	resulting variance	
U	voltage	
U_{fault}	fault voltage	
U_{meas}	measuring-circuit voltage	
$U_{int}(T_1)$	integration voltage at time T_1	
$U_{reference}$	reference voltage	
U_{output}	output voltage	
U_N	thermoelectric voltage of a standard cell	
V_{ref}	reference voltage at the Δ transformer	
V_{in}	input voltage at the Δ transformer	
W_C	charging energy of a capacitor	
W_L	magnetic field energy of an inductance	
$a_{o,i}$	upper limit for measured value x_i	
$a_{u,i}$	lower limit for measured value x_i	
g_1	local acceleration of gravity	
m	mass	
n	number of measured values	
t_1	integration period	
u	total error	
$\bar{v}_i$	arithmetic mean	
$v_{i,j}$	individual measurement (j=1...n)	
x_i	estimate of variable X_i from a series of n measurements	
α, β	temperature coefficients for a pressure balance	
λ_{Pe}	deformation coefficient	
ρ_M	mass density	
ρ_L	density of air	

4.4 Abbreviations

AD	German working commission for pressure vessels
AEF	Committee for units and dimensions in DIN
AFM	German working commission for measurement in production
AFNOR	French standards organization
AGR	German working commission for rationalization
AIF	German working commission of industrial research associations
AISI	American Iron and Steel Institute
	150 East 42nd Street, New York, N.Y. 10017, USA
ANS	American National Standard (formerly: USAS [see ANSI])
ANS	American Nuclear Society, 244 East Ogden Avenue, Hinsdale, Ill. 60521, USA
ANSI	American National Standards Institute,
	Inc. 1430 Broadway, New York, N.Y. 10018, USA (formerly: USASI)
ASA	American Standards Association (now: ANSI)
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
ASME	American Society of Mechanical Engineers
AUMA	Exhibitions and trade fairs committee of the German industry
AVI	Association of German iron and metal working industries
AWF	German committee for efficient production
API	American Petroleum Institute
BAM	German materials testing institute
BDI	Federation of German industry
BSI	British Standards Institution
BVS	German mining test laboratory (Dortmund)
BMA	German ministry of labour and social affairs
CEI	International electrical engineering commission
CEE	International commission for conformity certification of electrical equipment
CEN	European committee for the co-ordination of standards
CENELEC	European committee for electrotechnical standardization
CIPM	International committee for weights and measures
DAMG	German bureau of weights and measures
DBGM	German utility model
DBP	German patent
DECHEMA	German association of chemical process equipment
DGWK	German society for product marking
DIN	German standards institute
DK	Universal decimal classification
DKD	German calibration service
DVGW	German association of gas and water specialists
DVM	German materials testing association
DVS	German welding association
EC	European Community
EN	European standard
GS	Stamp of approval: "Tested for safety"
GVT	German process engineering research association
IEC	International electrotechnical commission
IFAC	International Association of Automatic Control

IP	International protection code
ISO	International Organization for Standardization
KTA	German nuclear technology committee
LN	German aviation standard
MKSA system	Metre-kilogram-second-ampere system
NAMUR	German working commission for measurement and control in the chemical industry
NIST	National Institute of Standards & Technologies
OECD	Organization for Economic Co-operation and Development
OIML	International organization for legal measurement
ÖNORM	Austrian standard
PTB	German physical and technical test institute
RAL	German committee for terms of delivery and quality assurance (part of the German standards committee)
REFA	German association for time and motion studies
RKW	Rationalization board of the German industry
SI	International units system
SNV	Swiss standards association
SUN	International Committee of Symbols, Units and Nomenclature
TEWI	Total equivalent warming impact
TRAC	Technical rules for acetylene systems and calcium carbide stocks
UL	Underwriters Laboratories Inc.® (USA)
UVVEN	German accident prevention regulations
VBG	Federation of German employers' liability insurance associations
VDE	Association of German electrical engineers
VDI	Association of German engineers
VDPG	Association of German physics societies
VdTÜV	Association of German technical inspectorates Address: Rottstr. 17, 45127 Essen
VDS	Association of property insurance companies
VG-Norm	German defense equipment standard
VSM	Standards published by the standards office of the association of Swiss machines.

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