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GUIDE TO PRACTICAL
TEMPERATURE MEASUREMENTS

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GUIDE TO PRACTICAL TEMPERATURE MEASUREMENTS

The work within OIML usually deals with metrology from the point of view of accuracy of instruments and standards. In practice, however, the results of measurements do not simply depend on the instruments but also on how they are used. In some fields of physics there may be a world between the value of the quantity or phenomenon aimed to be measured and the data recorded by the instrument or by the observer.

A typical field where influence factors and differences between the conditions of use and those of calibration frequently bring about false results, is temperature measurements.

There is an extensive literature on temperature measuring instrumentation as well as on theoretical thermodynamics. However, publications on the field in between i.e. on how to do correct temperature measurements are nowadays rare. Books on this subject are usually no longer available otherwise than from specialized libraries.

The technician, in particular in a developing country, who is faced with various aspects of testing or process control involving temperature measurements, is frequently unaware of the precautions to take and how to use correctly thermometers and temperature sensors.

The aim of this brochure is to explain in a very condensed form some fundamental techniques to be used for correct temperature measurements of solids, liquids and gases.

The text constitutes an amended reprinting of a brochure originally written for technicians employed in testing of mechanical and electrical finished products.

S.A. Thulin

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I. GENERAL CONSIDERATIONS CONCERNING TEMPERATURE MEASUREMENTS AND THERMOMETER CALIBRATIONS

I.1 Temperature scales and physical standards

Temperature indicates a state of energy.

The thermodynamic temperature scale can generally be represented by the simplified law for an ideal gas which at low pressures can be written

$$pV = nRT$$

where p = pressure, V = volume, n = number of moles of gas, R = molar gas constant ($8.31451 \text{ J mol}^{-1} \text{ K}^{-1}$) and T = temperature with respect to absolute zero.

This scale uses one single fixed point = the triple point of water, i.e. the point where water, its vapour and ice are in equilibrium. This state of energy is realized in a triple point cell, see Fig. 1. By convention the temperature of this point is set to exactly $T = 273.16 \text{ K}$ (Kelvin).

The temperature of the freezing point of pure water is about 0.01 K lower than its triple point.

To ensure high accuracy of the Celsius scale it has been agreed to set $0 \text{ }^\circ\text{C}$ at exactly $T = 273.15 \text{ K}$ of the absolute scale.

The relation between the Celsius scale (symbol t) and the Kelvin scale (symbol T) is thus exactly:

$$T = t + 273.15$$

A temperature difference has the same value on both scales and can therefore be expressed either in K or in $^\circ\text{C}$.

Gas thermometry generally involves pressure measurements at constant volume but is difficult to apply with the desired accuracy, especially at high temperatures.

Practical temperature scales have therefore been adopted at different times by the competent committees cooperating with BIPM. These scales are named after their year of application (1927, 1948, 1968 and 1990). The fixed points of these scales, preferably triple points and freezing points of various compounds, have assigned temperature values based on the best determinations of the thermodynamic temperature using gas thermometry, radiation thermometry or other methods involving thermodynamic concepts.

The official publications of BIPM concerning these scales also include the means of interpolation to be used between the fixed points, the related equations and necessary corrections.

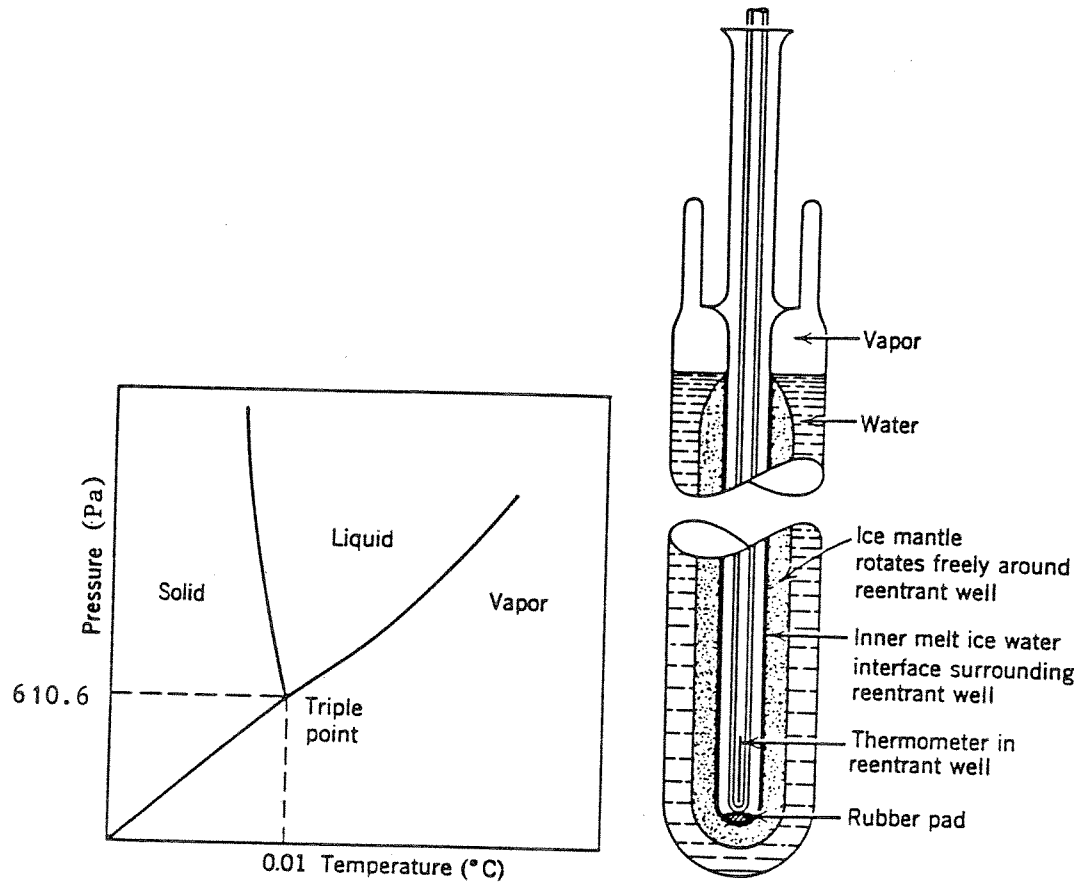


Fig. 1 - Water triple point cell and equilibrium diagram

The following means of interpolation are used in the International Temperature Scale (ITS-90) effective from 1 January 1990 :

- platinum resistance thermometry between 13.81 K (hydrogen triple point) and 962 °C (freezing point of silver)
- radiation thermometry according to Planck's law for temperatures over 962 °C.

This scale is extended below 13.81 K by use of helium gas thermometry.

The changes introduced by this scale with respect to the previous one (IPTS-68) are generally small and do not affect the practical measurements concerned in this brochure. However it should be noted that the temperature of the so-called normal boiling point of water at standard atmospheric pressure (101 325 Pa) is no longer exactly 100 °C but is close to 99.974 °C.

I.2 Thermal contact methods

Temperature measurements are frequently influenced by parasitic effects which can be considerably greater than the calibration errors of the instruments used.

Measurements are generally carried out at a particular spot or point in the media to be measured. This point must be located so that it represents from the geometrical view the mean temperature. The instrument located at this point must furthermore not change the value which was intended to be measured, i.e. by lowering or increasing the temperature.

I.2.1 Thermal contact, influence of thermal conduction

If the measuring point is located so as to be representative for the temperature to be measured it is still necessary to reach a good thermal contact between the media to be measured and the sensor of the temperature measuring device.

Temperature levels may be assimilated with electric potentials and temperature differences with voltage drops. A flow of heat Φ may be assimilated with a electric current and we obtain thus an equivalency to Ohm's law by writing

$$t - t' = R \cdot \Phi$$

where R is the thermal resistance.

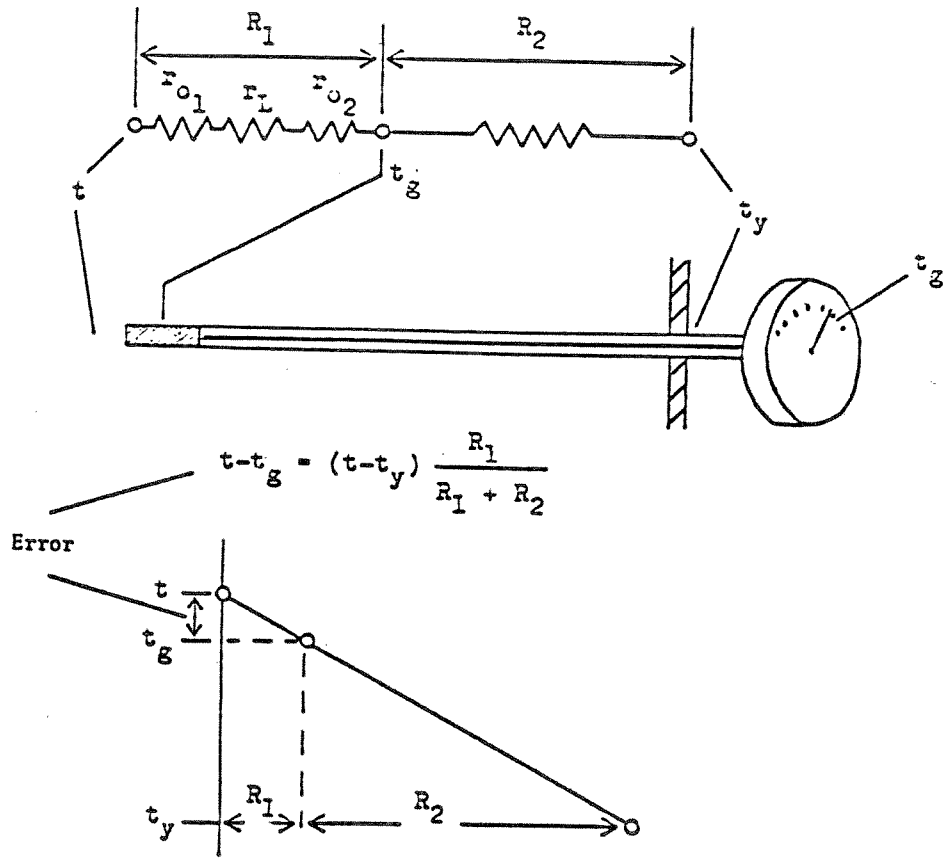


Fig. 2 - Influence of heat conductivity, symbolic comparison with electrical circuit

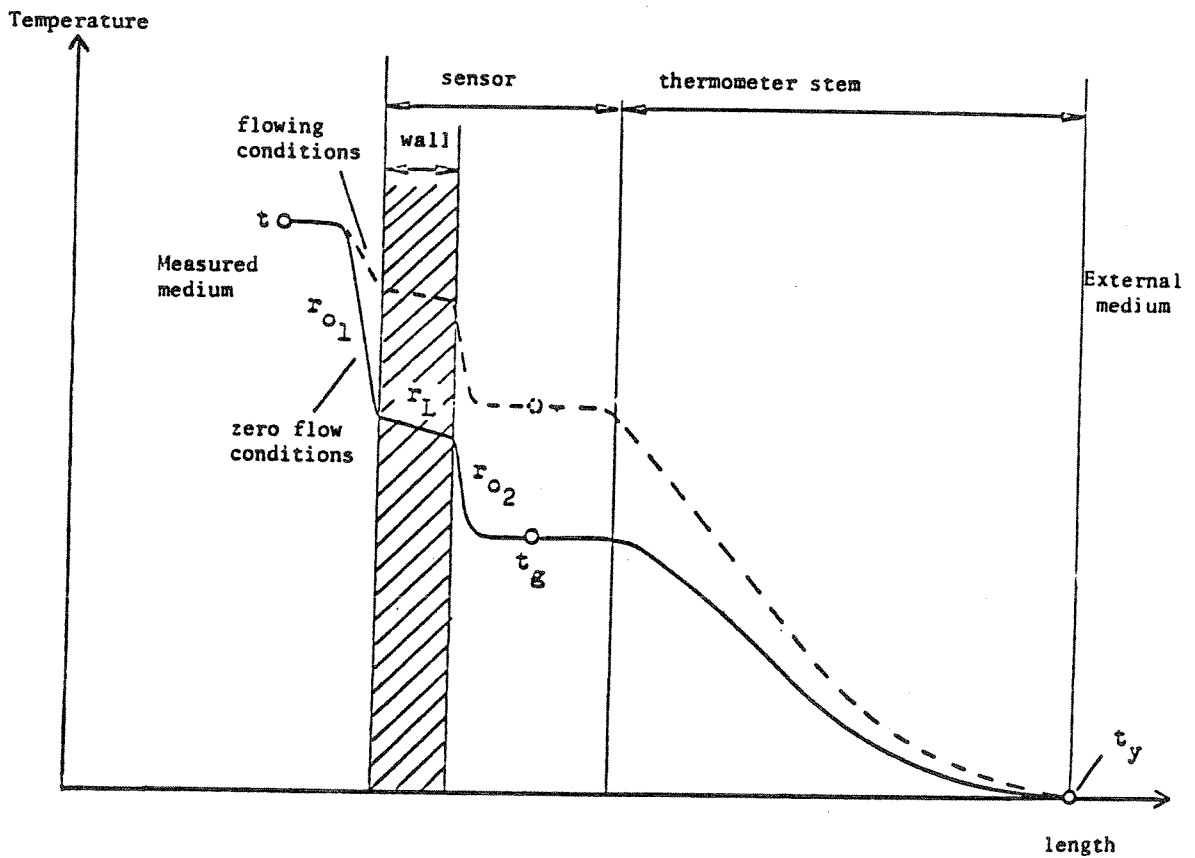


Fig. 3 - Symbolic representation of the temperature drop at a wall of a thermometer sensor, t = true temperature of medium to be measured, t_g = temperature measured by sensor.

In the case of contact measurements of temperature one may use the symbolic diagram in Fig. 2. The thermal resistance R_1 to the measuring medium should be low.

$$R_1 = r_{o_1} + r_L + r_{o_2}$$

where r_{o_1} is the transfer resistance between the medium and the protection tube of the thermometer.

$$r_{o_1} = \frac{1}{\alpha \cdot A}$$

α = thermal transfer coefficient depending on the liquid or the gas of the measuring medium and on the rate of flow

A = the surface of the protection tube exposed to the medium

r_L = thermal resistance of the protection tube

r_{o_2} = transfer resistance between protection tube and thermometer sensor.

Even when the protection tube is made from materials with low thermal conductivity such as stainless steel, glass, ceramics, the resistance r_L will usually be low compared to $r_{o_1} + r_{o_2}$ provided the protection tube is thin-walled. The temperature drop at the wall is illustrated in Fig. 3.

The thermal resistance R_2 against the surroundings should be high. This is accomplished by using long thin-walled protection tubes made from materials with low thermal conductivity. (Copper, brass and similar materials should never be used for such purposes). If the protection tube is fully immersed in the medium the difference $t - t_g$ will decrease with the depth of immersion following a hyperbolic law. This error may be estimated from the expression

$$t - t_g = f \cdot (t - t_y)$$

where the multiplier f may be obtained from Fig. 4 after computation of

$$X = \frac{\alpha}{\lambda} \cdot D \cdot \frac{L^2}{D^2 - d^2}$$

where D = external diameter of protection tube (in meters)

d = internal " " " "

L = length of " " "

Typical values of the thermal transfer coefficient α and the heat conductivity λ are given on the next page.

Typical values of the heat transfer coefficient α

	$W m^{-2} K^{-1}$	
boiling water	2000 - 6000 (depending on flow rate)	
water	200 - 5000 (*)	"
superheated water vapour	200 - 1500	"
air and fume gases	5 - 100	"
(*) α may be estimated as = $230 + 4200 C$ for water		
and as	$0.95 \cdot \frac{C}{v}^{0.87}$	for mineral oil
	$v^{0.435}$	

where C is the rate of flow in m/s and
v is the viscosity of the oil in m^2/s .

Typical values of the heat conductivity coefficient λ

	$W m^{-1} K^{-1}$
silver	420
copper	350
brass	150
duraluminium	160
soft steel	50
stainless steel	15
alumel	28
chromel	16
pyrex (and quartz)	1

Examples of calculation

- For a stainless steel tube with 5 mm external and 3.5 mm internal diameter, a heat transfer coefficient $\alpha = 200 W m^{-2} K^{-1}$ and a difference between internal and external temperature of $t - t_y = 100 K$ we obtain

depth of immersion	25	50	75 mm
difference $t - t_g$	6	0.15	0.005 K

(If the protection tube was made from copper the corresponding difference would have attained 20 K at the immersion depth of 75 mm).

- For a copper-constantan thermocouple using 1 mm copper wire we find that in an oil bath with $\alpha = 100 W m^{-2} K^{-1}$ the immersion length should be more than 150 mm if the error due to heat conductivity is to be less than 1 % of the internal to external temperature difference.

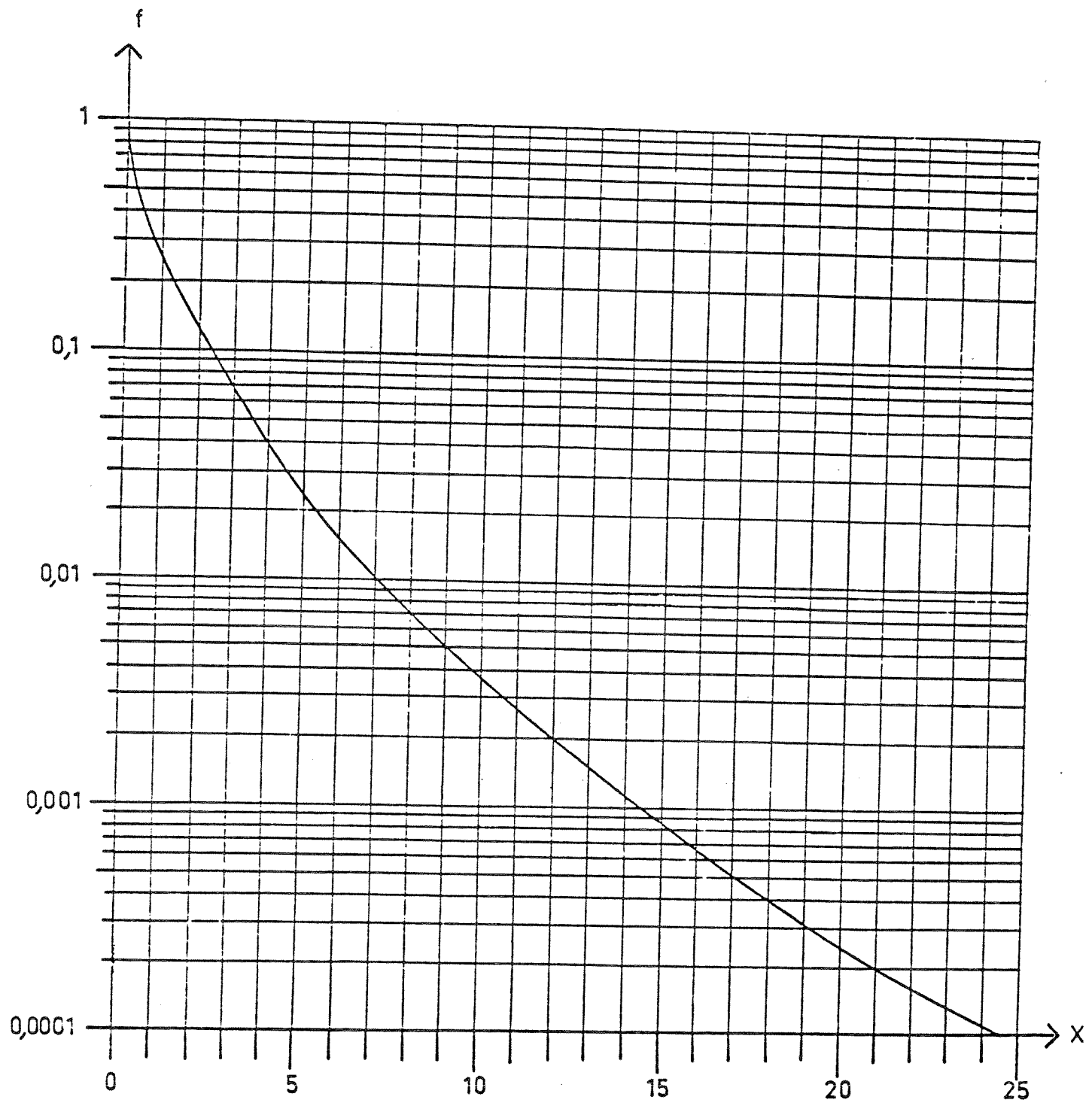


FIG. 4

1.2.2. Insertion of thermometers in the measuring media

Thermometers should whenever possible be introduced directly in the measuring medium. The use of special pockets influences precision and time constant considerably. If such pockets are necessary for protection purposes, high pressure etc they must be made from poorly conducting materials. Such pockets should not be filled with any liquid to improve the heat contact but their internal diameter should be adjusted to fit the diameter of the sensor of the thermometer, small tubes of copper or silver may be used for such adaptation purposes, these tubes should however be short and restricted to cover the sensitive part only.

One can sometimes reduce the error due to heat conductivity simply by thermal insulation of the insertion point.

1.2.3. Influence of radiation - measurement of gas temperatures

Heat radiation is absorbed heavily in most liquids and solids. The sensor part of the thermometer which is immersed in such media will therefore radiate as much energy as it receives.

In a gas the conditions of radiation are different. The sensor will radiate energy proportional to $\epsilon \cdot T^4$ and receive energy by radiation from surrounding surfaces in proportion g to $\epsilon \cdot T_y^4$. If the absolute temperature T_y is considerably lower than the absolute temperature T_g of the sensor, the resulting radiated power (proportional to $T_g^4 - T_y^4$) may be considerable compared to the energy which is transferred to the sensor through convection from the gas. The sensor should therefore have very low emissivity ϵ i.e. it should be highly reflective in the infrared region of the spectrum. For correct measurement of gas temperature it is necessary to surround the sensor by several high-reflecting screens separated from each other. In addition it is possible to increase the α -value by aspiration of the gas through these tubes (aspiration pyrometer).

Such screens are also necessary when particular radiation sources are present in the space where the temperature should be measured as otherwise the sensor will act as a radiation receiver and indicate a higher temperature than its surroundings. Thermometers which are used for measuring the temperature of the air in a room must therefore be protected from direct radiation from the sun or from other sources such as lamps etc.

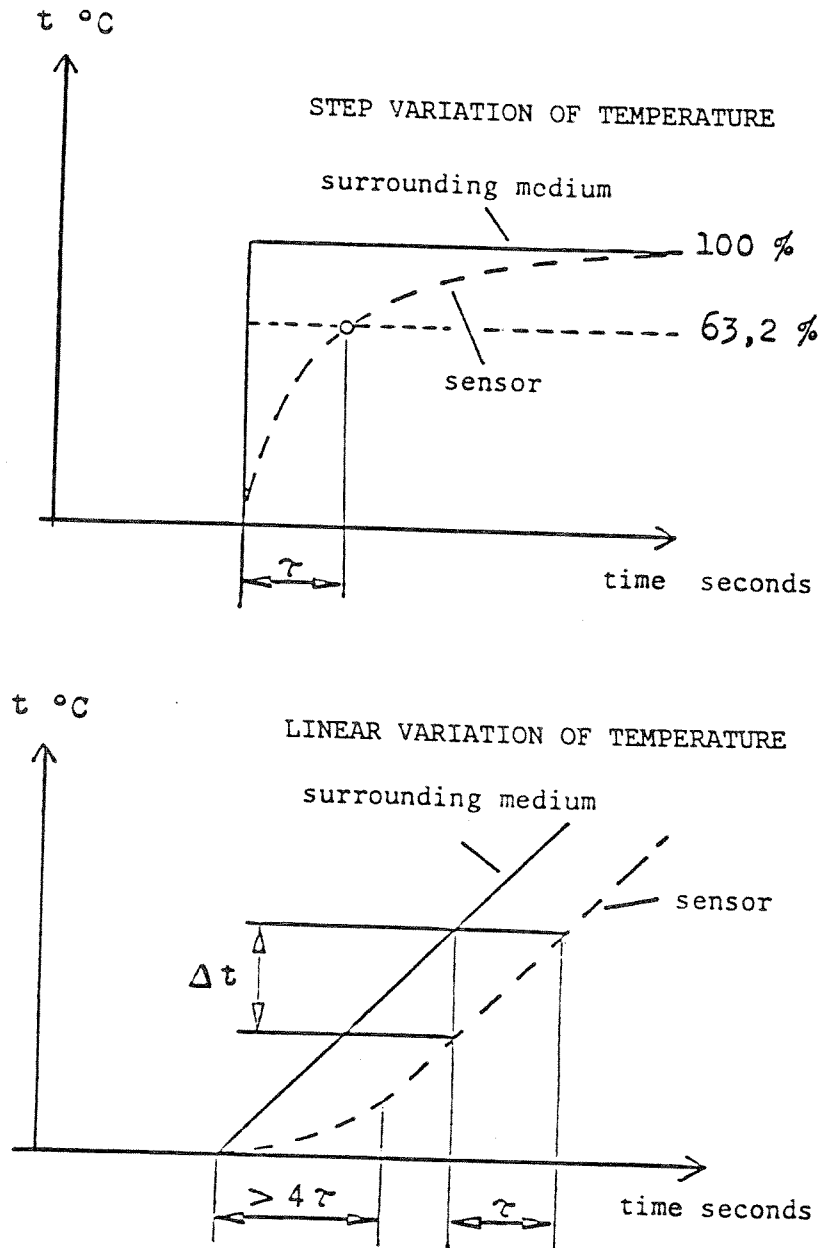


Fig. 5 - Time constant τ
 and temperature lag Δt

I.2.4. Influence of time constant, time lag

The temperature to be measured varies in most cases with time and it is necessary to take into account the time constant of the measuring device. This time constant is in most cases proportional to $R_1 Q_g$ where Q_g is the thermal capacity of the sensor. As R_1 depends mostly on the thermal transfer resistance between the protection tube of the sensor and the surrounding medium, the time constant will depend on the composition of the measured medium (gas or liquid) and on the rate of flow.

The time constant τ is the time which is required for a rapid step variation of the temperature to give an indication on the measuring device corresponding to 63.2 % of the temperature step. The time required to reach

99.9 %	of the temperature step variation	is	6.9 τ
99 %	" " " "	"	4.6 τ
50 %	" " " "	"	0.7 τ

(The last value gives the so-called half-time indicated by some manufacturers)

If the temperature is varied linearly and very slowly it will be found that the time constant τ will correspond to the time by which the indication lags the true value, see Fig. 5. The time constant for various media is generally indicated by manufacturers of thermometers and sensors, in other cases it is easy to determine it experimentally. For industrial types of thermometers and sensors the time constant may be considerable.

I.3 Temperature measurements using radiation

These are indirect methods based on Planck's law for radiation which can only be used correctly provided

- the radiating surface has an emissivity factor ϵ very close to 1.
- the emissivity factor is lower than 1 but well known at the same time as parasitic reflections from other sources of radiation are avoided through proper screening.

In cases where these conditions cannot be fulfilled the radiation detector will merely give indications which in an indirect way may be function of the temperature of the sighted surface which can be used for process control but not for correct determinations of temperature.

I.4 Measurement of surface temperatures

Surface temperatures are generally difficult to determine exactly due to the modifications at the measuring point that the measuring sensor introduces both through heat conduction and modification of the radiation properties. Variations in surface temperature can be determined by suitable radiation pyrometers suitably screened from parasitic reflections on the measured surfaces.

Surface temperatures on metal surfaces and similar can be determined with flat resistance sensors or thermocouples with fine leads which are applied and protected in such a way as to avoid modifications at the surface as regards heat conductivity, convection and radiation.

I.5 General considerations as regards calibration of thermometric devices

It is recalled that temperature set-offs or differences due to the type of installation and the means of measurement are frequently greater than the usual calibration errors which are treated below.

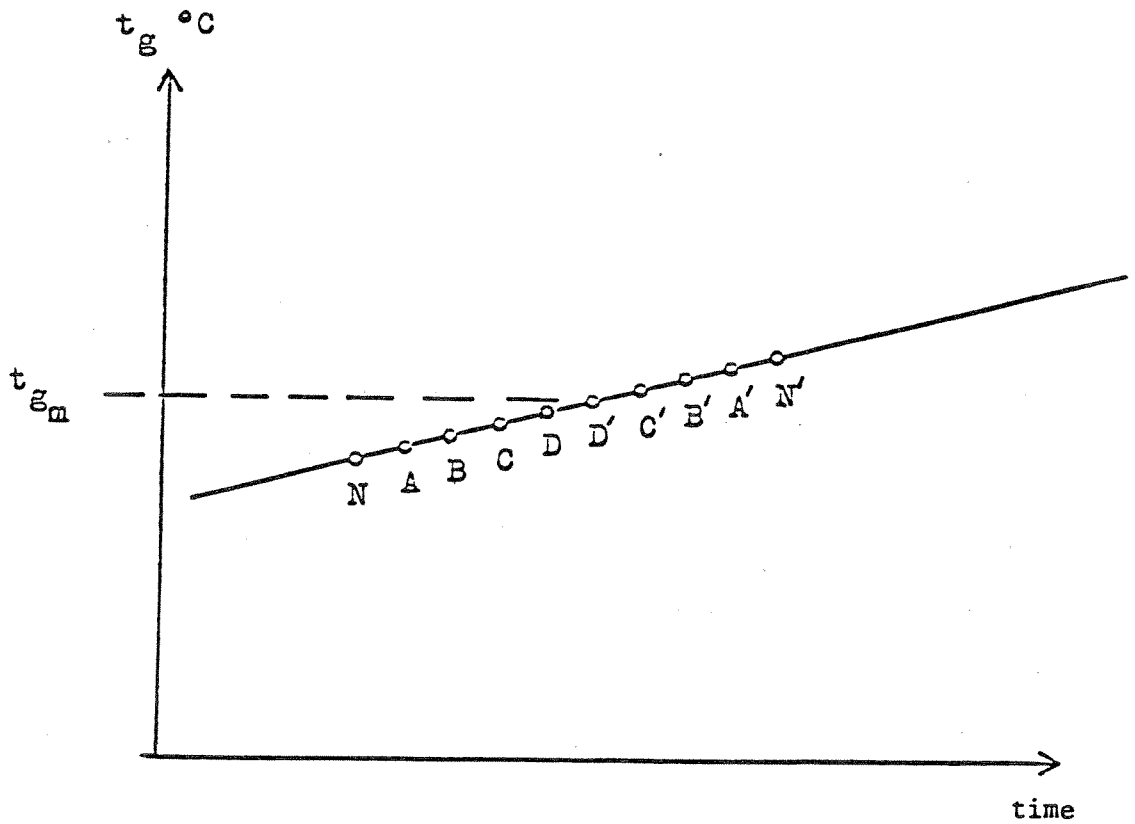
Temperature measuring devices should whenever possible be calibrated under identical conditions as those present during actual measurements (same immersion length, temperature drop, rate of flow of the liquid or the gas, etc). Temperature measuring devices are often used for determining temperature variations, in such cases the absolute temperature error is of minor importance provided it is kept constant.

Laboratory calibration of temperature measuring devices is usually done using stirred liquid baths. The thermometer tube should be immersed to the depth for which the calibration is intended to be valid. The temperature variation of the baths used should be very slow so as to avoid time lag errors. In cases where rapid calibration is required the standard used must be of identical construction as the thermometer to be calibrated so that the same time constants are obtained for both instruments.

Thermostated baths can be used but many times it is preferable to use baths where the temperature is varying very slowly. If the standard thermometer N is inserted in the middle of a group of for instance four thermometers A B C D, readings should be taken twice following the time scheme, see Fig. 6:

N - A - B - C - D - D - C - B - A - N

If measurements are made at equal time intervals the mean values for each thermometer will then correspond to the mean value of the two measurements on the standard N provided the time constant of N and the other thermometers are of the same magnitude.



$$t_{g_m} = \frac{N+N'}{2} = \frac{A+A'}{2} = \frac{B+B'}{2} = \frac{C+C'}{2} = \frac{D+D'}{2}$$

Fig. 6 - Calibration of thermometers in slowly varying temperature bath indicating order of readings of the thermometers A B C D and of the standard N

The zero point can be calibrated using a mixture of distilled water and ice (see Note below). To reach lower temperatures one may use a liquid bath of acetone in a Dewar bottle to which small quantities of solid carbon dioxide are added (dry ice). The stirring is obtained by bubbling air through the bath using a small pump similar to those used for aquariums.

Between 0 and + 95 °C one may use a water bath in which the thermometers are inserted in a large tube with forced water circulation from below. A similar arrangement may be used up to + 250 °C using silicon oil. Over this temperature it was customary to use salt baths up to + 500 °C but it is nowadays more convenient to use special calibration baths containing sand or alumina powder which is kept in steady motion by an air flow from below. From room temperature up to + 1200 °C one may with lower accuracy use a tube furnace containing a temperature equilibrating block made from copper, aluminium or nickel depending upon the highest temperature range required.

Note : The following description of an ice bath is reproduced from Liquid-in-Glass Thermometry by J.A. Wise, NBS Monograph 150 (1976) :

An ice bath can be easily assembled and consists of a container, a siphon tube, ice and distilled water. A Dewar flask, approximately 36 cm deep and 8 cm in diameter, can serve as a container for the ice. A vessel of this type is preferable, since the melting of the ice is retarded by the insulating properties of the Dewar flask. A siphon is placed in the flask to enable excess water to be removed as the ice melts. The clear or transparent portion of commercially purchased ice, or ice made from distilled water, can be used. The ice is shaved or crushed into small chips measuring 2 to 5 mm. The flask is one-third filled with distilled water and the shaved ice is added. This mixture is compressed to form a tightly packed slush and any excess water is siphoned off. Before the bath is used, adequate time (15 to 30 min.) should be given for the mixture to reach a constant temperature throughout.

Ideally there should be as much ice in the flask as possible, with the small spaces between the chips filled with distilled water. It will be necessary periodically to add ice and to remove the excess water while the bath is being used to maintain this ideal consistency. If care is taken to prevent contamination of the ice and water, the ice point can be realized to better than 0.01 °C by this means.

II. LIQUID-IN-GLASS THERMOMETERS

II.1 Types of execution

There are a very great number of executions of liquid-in-glass thermometers depending on their intended use. The sensitive part or the container is usually made from special so-called hard glass, quartz is used for high temperatures. The usual liquid is mercury at medium temperatures, mercury with high pressure gas at higher temperatures and organic liquids such as alcohol, toluene and pentane at low temperatures. In addition gallium-filling may be used up to 1000 °C and mercury-thallium alloy at low temperatures down to - 56 °C. Mercury freezes at - 38.9 °C.

Thermometers with organic liquid filling have usually low accuracy mainly due to the fact that the liquid is wetting the inside of the capillary tube.

II.2 Reference point

For accurate temperature measurements, 0.1 K or better, the thermometer should be chosen so that it has a reference point, usually the ice point 0° C.

The container, or reservoir, has in fact the tendency of changing its volume with time (ageing) so that all values on the scale are shifted by up to 0.1 K or sometimes more. By determining the value of the ice point it is possible to apply a correction without the need for a full recalibration of the other divisions. However, high temperature thermometers which are used over 350 °C may show changes also in the capillary which require a recalibration of the full scale.

II.3 Hysteresis or zero depression

If very accurate measurements are to be made with mercury thermometers it is necessary to take into account the hysteresis which takes place in the glass between heating up and cooling down. This hysteresis depends on the glass used and amounts generally to at maximum - 0.001 K for each degree that the thermometer has been heated just before the measurements over the temperature finally read on the thermometer. The hysteresis disappears after 1 to 5 days at constant temperature. The influence of hysteresis is null if only continuously increasing temperatures are measured.

II.4 Influence of the bore of the capillary

Precision mercury thermometers should not be divided in less than 0.1 K divisions. If the diameter of the capillary is decreased to increase the sensitivity there is great risk that the accuracy is affected by the capillary forces. The mercury column then moves in small jumps.

In calibration or accurate measurements of sensitive mercury thermometers it may prove necessary to give small shocks to the stem with a pen or similar object so that the mercury comes into a mean value position.

II.5 Influence of pressure

The influence of external pressure on precision mercury thermometers is of the order of +0.1 K per atmosphere. The influence of the internal pressure is of the same order. The effect of the latter is that the readings between vertical and horizontal positions of the thermometer differ by some 0.01 K.

II.6 Time constant, temperature lag

The time constant for precision thermometers when used in well stirred water baths is $\tau = 2$ to 10 s and is usually not troublesome as long as the time variation of the temperature is small. If the temperature variation is 2 K/min and the time constant 6 s the temperature lag will be

$$\frac{2}{60} \cdot 6 = 0.2 \text{ K}$$

In air without draft the time constant is however 30 to 50 times greater. Therefore if the time variations of temperature are great it is necessary in such cases to provide the thermometer with a ventilation device increasing the air flow so as to reduce the time constant. For air temperature measurements it is also necessary to provide for a radiation shield around the reservoir consisting of a polished metal tube with not too small internal diameter.

For certain types of industrial thermometers it must be taken into account that not only the reservoir has a time constant but also the mercury in the stem. The latter may be much greater as it is not immersed in the streaming media. For such thermometers when used in so-called dip thermometry it may be required to take the measurements always after the same time that it is taken out of the liquid, e.g. 1 minute after, in order to obtain reproducible results.

II.7 Influence of the immersion depth

In precision measurements with mercury thermometers it is necessary to take into account the temperature of the mercury column which is outside the measuring medium. There are three cases of immersion as shown in Fig. 8. The expressions "total" and "partial" immersion refer to the liquid column and not to the thermometer itself. If the thermometer is completely immersed in the liquid bath, the terminology is "complete" immersion. From the calibration point of view the latter (apart from pressure effects) is equivalent to total (or full) immersion.

Precision thermometers are usually calibrated for total immersion in vertical

position. For thermometers which are calibrated for partial immersion, the immersion depth is usually indicated (76 or 100 mm). The latter calibration supposes that the free part of the thermometer stem is at a certain mean temperature which should be indicated (such as 20 or 25 °C). If the external temperature is different from the calibration conditions, the indication of a partial immersion thermometer may be in error by an appreciable amount.

For a total immersion calibrated thermometer it is possible to determine the correction which has to be added to the indicated value when the thermometer is used with partial immersion as follows

$$\text{correction} = K \cdot n \cdot (t - t_u)$$

where the factor K depends on the glass of the thermometer and is usually about 0.0016 for Celsius-calibrated mercury thermometers and about 0.001 for glass thermometers using organic liquids such as alcohol.

n = degrees of the mercury column which is external to the measuring medium or liquid.

t = temperature of the liquid reservoir

t_u = mean temperature of the external part of the mercury (or organic liquid) column

The latter temperature may be difficult to appreciate unless an additional thermometer is fixed to the stem of the main thermometer.

According to the above formula it will be found that for a thermometer which is calibrated for full immersion and reads 100 °C when immersed only to the 20° C-division the correction will be if $t_u = 50$ °C:

$$0.0016 \cdot (100 - 20) \cdot (100 - 50) = 0.64 \text{ K.}$$

Note that thermometers for which the divisions start at higher temperature than normal ambient temperature usually have a contraction chamber before the division starts (see Fig. 7). For such thermometers there may be a risk for important errors if the depth of immersion is different between calibration and measurements.

II.8 Various defects, loose scales, separated column etc

Precision thermometers usually have an engraved (etched) stem) in front and an enamel layer as backing. Other thermometers and in particular those which are very sensitive (but not necessarily accurate) often have a separate scale enclosed in a protection tube. For such thermometers it is necessary to check that the scale does not move.

Before measurements it is necessary to check that the liquid column has not separated during transport or otherwise (especially for thermometers with

contraction chambers). If this is the case it is first necessary to see if the thermometer has an expansion chamber on top of the scale. In the affirmative it is possible to heat the thermometer reservoir until the separated part is joined by the liquid column. In other cases one may cool down the reservoir with ice and shake down the separated column by knocking the reservoir against a soft support.

Important: If the thermometer has no expansion chamber on top of its scale the thermometer should never be used or heated at higher temperatures than for which it is intended as otherwise it will be destroyed due to the internal pressure (take into account also the time constant).

Thermometers containing organic liquids should always be stored in vertical position.

II.9 Tolerances, accuracy and corrections

The following table gives an idea of the best accuracy which can be obtained with mercury-in-glass thermometer of the precision type:

Range $^{\circ}\text{C}$	<u>Total immersion type</u>			
	Division	Construction tolerances	Accuracy obtained with all corrections applied	Corrections stated to (in certificates)
	K	K	K	K
0 - 100	0.1	0.3	0.01 - 0.03	0.01
0 - 150	0.2	0.4	0.02 - 0.05	0.02
0 - 150	0.5 (or 1)	0.5	0.1 - 0.2	0.1
0 - 200	0.2	0.5	0.05 - 0.1	0.02
0 - 300	1	1	0.2 - 0.3	0.1
0 - 500	2	2 - 4	0.5 - 1	0.2

<u>Partial immersion type</u>				
0 - 100	0.5 (or 1)	1	0.1 - 0.3	0.1
0 - 300	1	1.5	0.5 - 1	0.2
0 - 500	1 (or 2)	5	1 - 2	0.5

For thermometers using organic liquids such as alcohol the construction tolerances are of the order of 1 to 2 K for thermometers divided in 1 K intervals and the accuracy is at best 0.5 K when using corrections. The certificate corrections for such thermometers are usually stated to 0.1 K at best.

II.10 Other thermometers using thermal expansion

Bimetallic thermometers with a circular indicator are frequently used, their

accuracy is low. Remote measuring thermometers using a liquid reservoir containing toluene, alcohol or mercury and a capillary connected to a spring loaded pointer manometer indicator are also frequent. The accuracy of such devices is of the order of 1 to 2 % of full scale. They are usually calibrated for a given ambient temperature. For capillary conduits with mercury filling the influence of the ambient temperature is of the order of 0.1 to 0.2 % of full scale for a change of ambient temperature of 10 K. Capillary tubes of this type must be installed so that they are protected from heat sources. This is also the case for vapour-pressure thermometers in which the pressure from the measuring bulb is transmitted to the indicating manometer through a liquid-filled capillary tube.

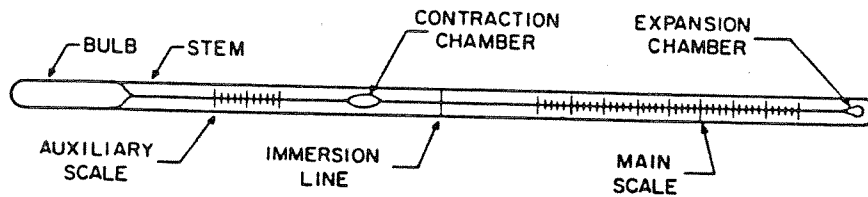


Fig. 7 - Precision liquid-in-glass thermometer

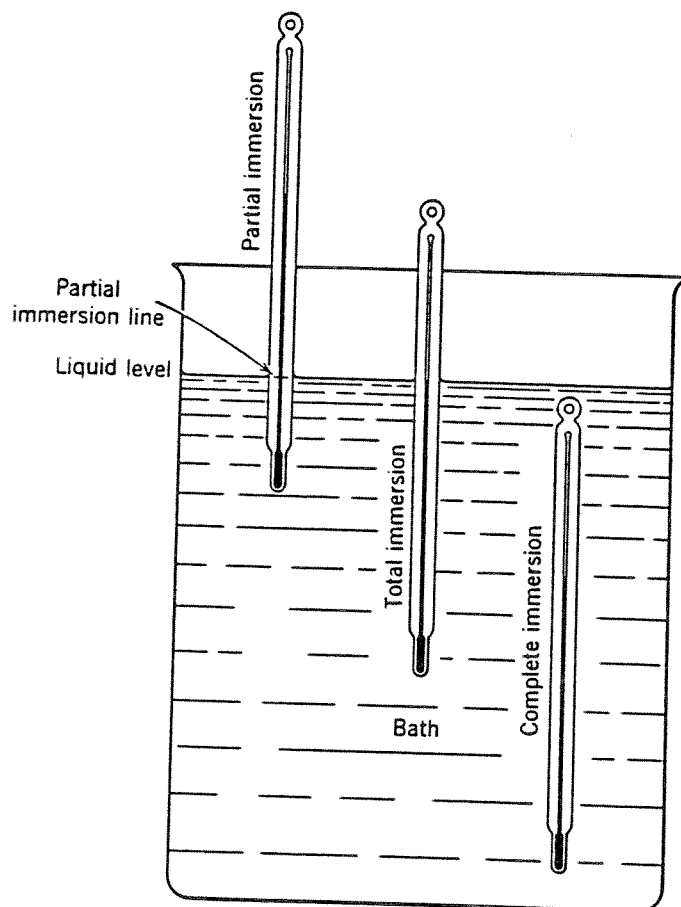


Fig. 8 - Definitions of the immersion depth of thermometers

III. THERMOCOUPLE MEASUREMENTS

III.1 Basic principles

The joint of two metals gives rise to an electric potential which depends on the temperature of the junction. As two junctions always are required when connecting an electrical instrument this will result in a potential difference which depends on the difference of temperature of the two junctions. One of the junctions is in most cases kept at an approximately constant temperature and is called reference junction (or sometimes "cold" junction).

The potential difference is usually measured by a compensating potentiometer so that the current in the leads is practically null which is indicated by a null detector. Potentiometer recorders are often used which operate on the same principle.

Digital voltmeters with sufficient sensitivity are also used nowadays, their internal resistance is usually so high that the influence of lead resistance in the thermocouple wires can be neglected.

III.2 Use of analog millivoltmeters

For medium accuracy work especially in connection with furnaces one uses in most cases a so-called millivoltmeter which is in fact a moving coil milliamperemeter calibrated in millivolts. In some cases the millivoltmeter is calibrated directly in degrees on condition of using a certain type of thermocouple such as iron-constantan. Some types of point recorders using a pointer and a printing bar operate on the same principle but may be equipped with a preamplifier in certain cases.

With all these types of instruments it is necessary to check that their internal resistance is high compared to that of the thermocouple leads. In many cases such instruments are calibrated for a certain external resistance such as 10 or 20 ohm or adjustment devices may be provided so as to take into account the effective resistance of the thermocouple circuit. If no adjustment of the circuit resistance is provided it is possible to obtain the correct millivolt-value by multiplying the reading by the factor

$$C = \frac{R_y + R_i}{R_e + R_i}$$

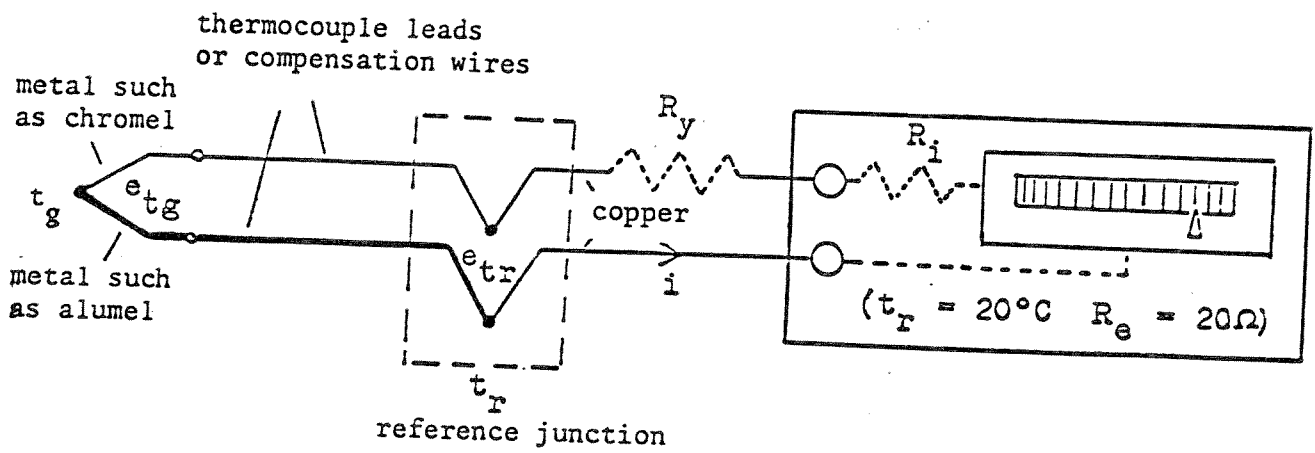
where

R_y = measured external resistance of the thermocouple circuit up to the connections on the millivoltmeter

R_i = internal resistance of the millivoltmeter (usually indicated)

R_e = external resistance for which the millivoltmeter is calibrated as indicated on its scale (usually 10 or 20 ohm)

If the internal resistance is not indicated it can be determined by switching in a resistor of 100 ohm in series with R_y . From the readings with and without this resistance it is possible to determine R_i .



Potential difference $e = e_{tg} - e_{tr}$

Fig. 9 - Measurement of thermocouple voltage using millivoltmeter

The resistance of copper leads varies with 0.4 % per degree, therefore if these leads are subject to considerable temperature variations this may have to be taken into account.

The reference junction or the "cold" junction should be kept at stable ambient temperature in a metal block the temperature of which may be measured with a mercury thermometer. Industrial measuring devices such as potentiometer recorders usually have a provision for compensation of the ambient temperature of the reference junction either by enclosing it in a thermostated box or by the use of a bridge circuit containing a temperature sensitive resistor (copper or thermistor) which provides a compensating voltage applied in series with the thermocouple voltage.

The reference junction may be installed close to the measuring point so that thick copper wires may be used for the millivoltmeter which then can be placed at some distance. In cases where this is not practical such as in factory installations one uses frequently so-called compensating leads which consist of leads of two alloys which have the same thermoelectric force as the thermocouple used but which are less expensive and may be made to have larger diameter and lower total resistance.

The thermoelectric force is usually not a linear function of temperature. The true temperature is usually obtained from calibration tables or standard tables using the millivolt-value measured or calculated if corrections for the lead resistance have to be applied. The thermocouple tables are usually established for a temperature of the reference junction of 0 °C.

If the measured (and corrected) value on the millivoltmeter is e mV, the true temperature of the measuring thermocouple can be found in the table by using the value e_{t_g} calculated from

$$e_{t_g} = e + e_{t_r}$$

where

- e_{t_g} = millivolt-value corresponding to the temperature to be measured
- e = observed millivolt-value (C-factor corrected if required)
- e_{t_r} = millivolt-value for the reference junction obtained from the thermocouple table

The calibration of thermocouple devices can be made by comparison using a tubular furnace with equilibrating metal block and arranging so that the thermocouples to be compared are in best thermal contact with each other. In most cases however one uses thermocouples without particular calibration by relying upon the standard table supplied by the manufacturer of the thermocouple wire. The table on the next page states ranges of use, manufacturing tolerances with regard to standard tables and the accuracy which may be reached at best by individual calibration.

III.3 THERMOCOUPLE RANGES AND ACCURACIES

Type	Usual range (1)	Usual tolerances from standard table (2)	Accuracy when individually calibrated (3)	Thermoelectric force $\mu\text{V}/\text{K}$
T Copper-constantan	- 250 to + 400 °C	± 1 K from 0 to 100 °C ± 1 % 100 to 400 °C	0.1 K 0.2 K	39 at 0 °C 58 300 °C
J Iron-constantan	- 200 to + 850 °C	± 3 K from 0 to 300 °C ± 1 % 300 to 850 °C	0.5 K 1 K	50 at 0 °C 56 500 °C
E Chromel-constantan	- 200 to + 850 °C	± 3 K from 0 to 400 °C ± 0.75 % 400 to 850 °C	0.5 K 1 K	59 at 0 °C 81 500 °C
K Chromel-alumel	- 200 to + 1100 °C	± 3 K from 0 to 400 °C ± 0.75 % 400 to 1100	0.5 K 1 K	40 at 0 °C 43 500 °C
S Platinum - 90 % platinum 10 % rhodium	0 to 1400 °C	± 1 K from 0 to 1100 °C ± 2 K 1100 to 1400 °C	0.5 K 1 to 2 K	6 at 0 °C 12 1000 °C

Notes :

(1) The highest temperatures indicated are valid only for wire diameters of 1 mm or more.

(2) The tolerances are given only as an indication. In some cases narrower limits can be obtained over a more restricted temperature range (the publication of the International Electrotechnical Commission IEC 584 defines three accuracy classes).

(3) for thermocouples which are new and have not been in contact with other materials at high temperatures or used in corroding atmospheres.

III.4 Heat treatment and ageing

Thermocouples are usually spot-welded or silver-soldered. Before use or calibration they should be heated to a somewhat higher temperature than they will be used for and then slowly cooled down in order to take away strain in the leads which may create parasitic emfs.

Thermocouples which are used at high temperature undergo chemical-physical reactions and structural changes which make that such thermocouples must be checked or replaced at a frequency which only experience may show and depends on the presence of ambient corrosive atmosphere, etc. This is in particular the case for thermocouples made from thin wires, below 1 mm.

Thermocouples should not come into contact with molten metals. Silicon and carbon should not come in contact with Pt-Pt Rh - thermocouples. The protection tubes to be used must be selected in accordance with the indications of the manufacturer.

III.5 Electrical insulation

When using electrical sensors such as thermocouples as well as resistance thermometers one must ensure that the electrical insulation is good. The insulation with respect to earth can easily be measured but is in most cases of minor importance provided the installation is not particularly sensitive to earthing defects. The insulation between the leads can be more than adequate at low temperature but defective at high temperature. Double bore ceramic(alumina) tubing should be used for the thermocouples at high temperature.

III.6 Influence of heat conductivity, measurement of surface temperatures

The heat conductivity of the thermocouple wires can never be neglected and can frequently create considerable errors in the measurements especially when the measuring junction cannot be brought in good thermal contact with the medium or surface to be measured. At low temperatures (below 200 °C) and when there is no risk for chemical reactions (oxidation or reduction) one may use thin wires, 0.5 mm or lower. The leads to the junctions should be placed in such a way as to diminish the temperature gradient along the wire (slow temperature variation along the length of the wire).

If it is required to measure the temperature inside a piece of metal, the length of the hole for the thermocouple should be 10 times the diameter. The insulated leads should in addition be held for a length of 50 mm or more close to the metal surface in a slowly varying temperature field. An example of such an arrangement is shown in Fig. 10.

If the surface temperature is to be measured it is necessary to take certain precautions as illustrated in Fig. 11.

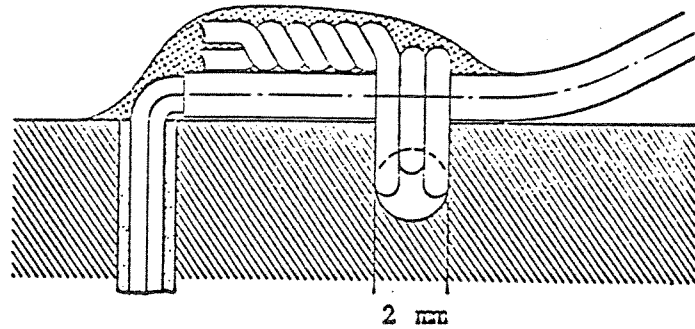


Fig. 10 - Method for fixing thermocouples to rigid bodies using two V-shaped holes and tightening compound (according to Baker & Ryder)

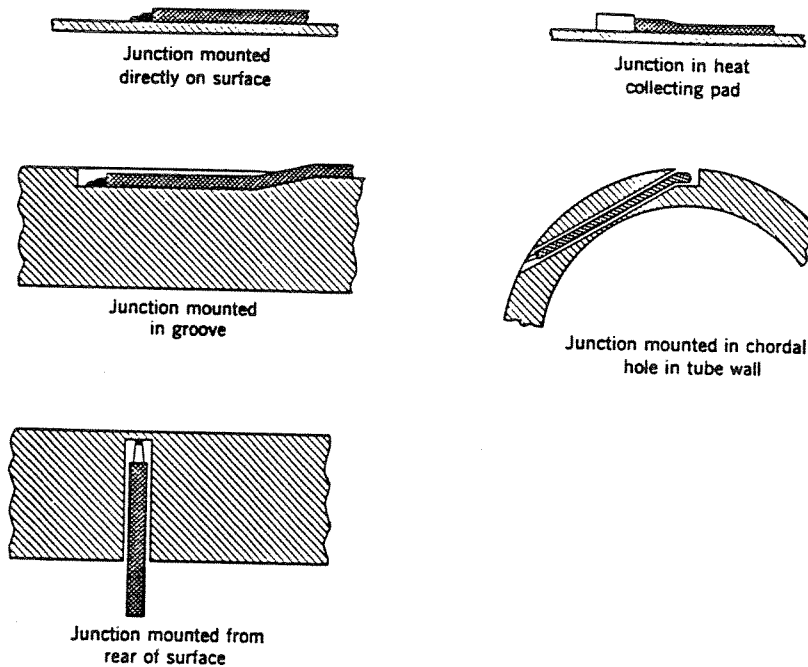


Fig. 11 - Methods for fixing thermocouples to rigid bodies for surface temperature measurements (according to A.J. Otter)

Another arrangement which has been used for measuring surface temperatures of electric irons is shown in Fig. 12. This device consists of a thin silver disc, 10 mm in diameter and 2 mm thick, which has a slightly concave contact surface, to which thermocouple wires with 0.35 mm diameter or less are silver-soldered (brazed). The disc is pressed towards the surface to be measured with a spring using a force of 5 newton (0.5 kgf) or more. Tests with this device have shown that the error due to heat conductivity can be brought down to 2 K at 300 °C.

IMPORTANT : When soldering or silver-soldering thermocouples it is necessary to check that alloyed metal does not float up along the wires, the whole junction must be placed at the temperature to be measured.

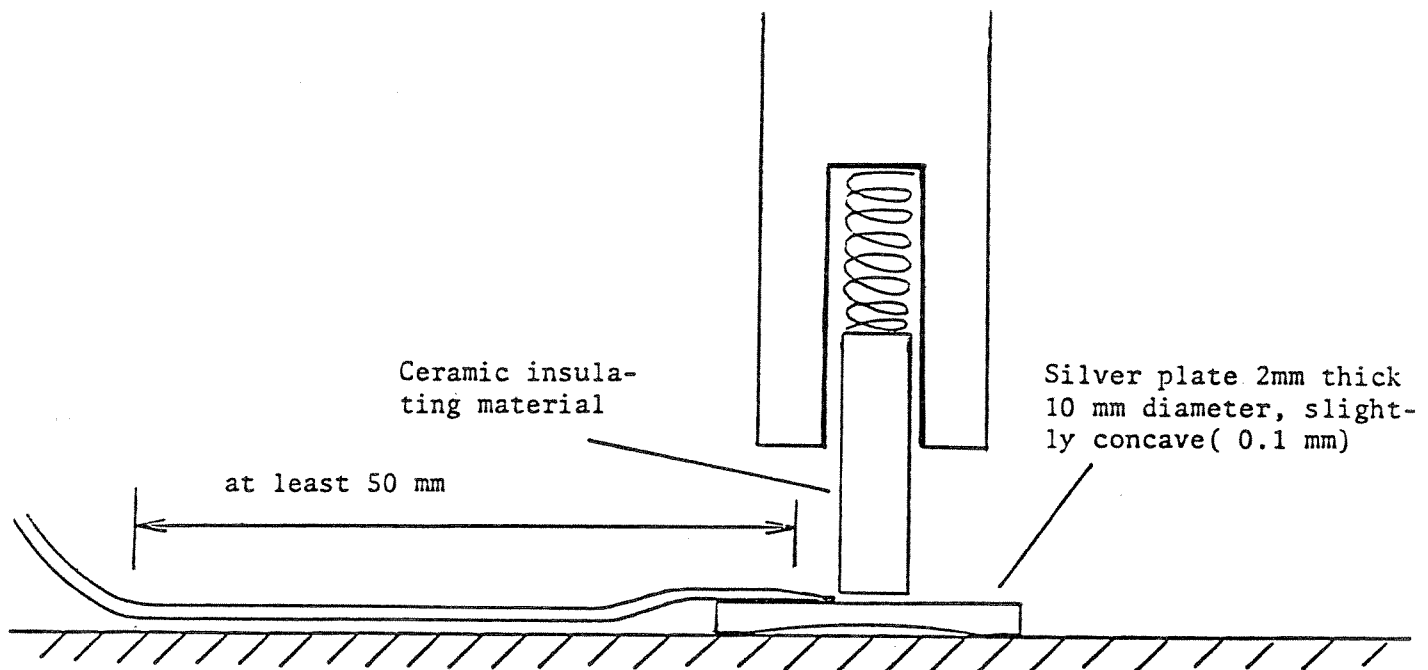


Fig. 12 - Measurement of surface temperature with spring loaded silver plate

IV. RESISTANCE THERMOMETRY

IV.1 Basic principles

Resistance thermometry is over a large span of temperatures presently the most accurate technique for measuring temperatures. The sensors normally used are made from platinum, copper, nickel, germanium or mixtures of metal oxides (thermistors).

For metals the variation of resistance with temperature follows in most cases a law which within a limited range can be expressed approximately as

$$R_t = R_0 (1 + At + Bt^2)$$

where R_0 is the ice resistance i.e. the resistance at 0 °C and A and B are coefficients which depend on the metal. In some temperature regions this formula has to be completed with an additional term Ct^3 .

For platinum the coefficients are approximately $A = 3.97 \cdot 10^{-3}$ and $B = -0.58 \cdot 10^{-6}$. For copper the B-coefficient can be neglected and the resistance follows approximately a linear law with $A = 0.4$ % per degree.

For nickel the B-coefficient is positive and the A-coefficient is high about $5.6 \cdot 10^{-3}$ but the behavior of this metal above 200 °C is more irregular. The exact temperature dependence of the resistors must be determined individually as it depends on the composition (purity) of the metal, mechanical strain on the wire, type of support etc.

IV.2 The standard platinum resistance thermometers

These instruments are the basic interpolation means in the International Temperature Scale between 13.81 K to 962 °C. The most common long stem type has usually an ice resistance of $R_0 = 25$ (or 25.5) ohms and can be used between the limits of - 200 and + 550 °C. For cryogenic work down to the triple point of hydrogen the platinum resistance thermometer is usually made in the form of a short capsule. Temperatures up to 1000 °C can be measured by special thermometers which have a very low ice resistance (0.25 ohm to 2 ohm) so as to diminish problems with insulation at high temperatures. The purity of the platinum of standard thermometers should be such that the ratio between the resistance at the boiling point of water and the ice resistance is higher than $R_{100}/R_0 = 1.3925$. The interpolation formulas between the fixed points and the corrections to be used with this type of thermometer are published by the International Bureau of Weights and Measures (BIPM).

Such instruments are usually accompanied by a computed table giving R_t/R_0 - values as a function of temperature established from calibration at selected fixed points. Interpolation between values in such tables allows direct evaluation of the temperature. The stability of R_t/R_0 - values for the best standard platinum thermometers approaches 0.001 K per year at

ambient temperatures but the ice resistance R_0 may have to be determined more frequently using a triple point cell (see Fig. 1).

The standard platinum resistance thermometers usually have a sheathing of fused silica (quartz) though some constructions (substandards) exist which use stainless steel sheath. Standard platinum thermometers have the resistance wire freely mounted on small books so as to avoid strain, they must therefore be handled with great care and are practically only used for calibration of other thermometers or for some precision measurements of material constants.

IV.3 Industrial platinum resistance sensors

These have a much more rugged construction: the wire is either wound on a core which has approximately the same coefficient of thermal expansion as platinum or each spire of the resistance coil is fixed with a binding material (glass) on a part of the diameter so that the wire can expand freely along its diameter. These sensors are also protected from the environment by a glass sealing or glass enamel. The most frequently used standardized value of the ice resistance is $R_0 = 100$ ohms. Duplicate constructions exist consisting of two 100 ohm sensors in the same envelope allowing one of the sensors to be used for process control and the other one for measurement of the temperature obtained. Industrial platinum resistance sensors allow below 500 °C more accurate measurements than thermocouples and there is no problem with reference junctions but the zero value R_0 may have to be checked from time to time at the same time as the zero of the measuring devices used.

For low and medium accuracy measurements it is generally possible to rely upon the standard calibration tables furnished by the manufacturer giving $R_t = f(t)$ along with tolerances for the resistance values. It is particularly important however to check the zero resistance before use and an ice bath using distilled water should be available for such purposes. The accuracy in using this procedure is about 0.2 to 2 K depending on the temperature range. It should be emphasized that the standard tables for platinum resistance sensors published by standard organizations do not always represent the closest fit to the actual sensors as the manufacturers may use different materials both for the wire and for supporting it with the result that the R_{100}/R_0 - values can vary from the standardized value of 1.385 (alloyed platinum) to 1.392 (pure platinum). For best accuracy it is suitable to use some form of calibration baths and a standard platinum resistance thermometer as reference allowing individual tables $R_t/R_0 = f(t)$ to be established. If this procedure is adopted it is possible with some types of ruggedized platinum resistance sensors to obtain a very high accuracy (0.01 K at ambient temperatures). The sensors should preferably be cycled first between the two extreme temperatures between which they are to be used(1)

(1) Thulin A. - High precision thermometry using industrial resistance sensors, Journal of Scientific Instruments, 1971, 4, p.764-768.

IV.4 Thermistors

Thermistors are thermal-sensitive resistors which are made from semi-conducting compounds, usually composed of metal oxides. Their resistance usually decreases with temperature following an exponential law. At room temperatures the temperature coefficient is thus negative and most times about ten times higher than that of platinum. There are usually no standardized values of the ice resistance for such sensors, their normal range of temperatures extends from -50 to $+150$ °C and stabilities of the order of 0.01 K per year can be reached for some types when kept at room temperature. They are frequently used in temperature regulating devices.

IV.5 Measuring bridges and influence of lead resistance

The resistance of resistance thermometers is usually measured by bridges though it is in principle possible to use devices such as digital ohmmeters, crossed-coil ohmmeters etc. The need for compensating the null resistance R_0 at a fixed temperature (0 °C) makes bridges more suitable. The drift with time of the components of such bridges can usually be overcome if the sensor can be calibrated together with the bridge at a fixed temperature (0 °C) at regular intervals as it is only required to establish ratio values R_t/R_0 through the bridge measurements and not absolute values of resistance.

One problem is common to both high precision measurements with standard resistance thermometers and medium precision measurements with industrial sensors: care must be taken so as to avoid the influence of resistance variations in the leads of the sensor. These leads are usually made from copper which has a temperature coefficient of about 0.4 % per degree thus of the same order as for platinum. The lead resistances must thus be kept small compared to the resistance of the sensor. When an accuracy of 0.5 K or better is required it is usually necessary to use sensors which have four-terminal leads and bridges which are suitable for such measurements.

For resistance measurements with standard platinum resistance thermometers double bridges such as the Kelvin bridge or the Smith bridge type III were frequently used. The theory of operation of this bridge is explained in Fig. 13. The lead resistance can also be compensated in using a Wheatstone bridge and two measurements with a reversal of the position of the thermometer as explained in Fig. 14, this method is used in the well-known Mueller-bridge. A similar method can be used without reversal of the thermometer but by using a simple toggle switch and an auxiliary resistor R_s as explained in Fig. 15.

Modern automatic bridges use inductive techniques (DC current comparator or low frequency AC inductive dividers) for accurate measurement of the resistance ratio with respect to a standard resistor. Potentiometric comparison methods are also used.

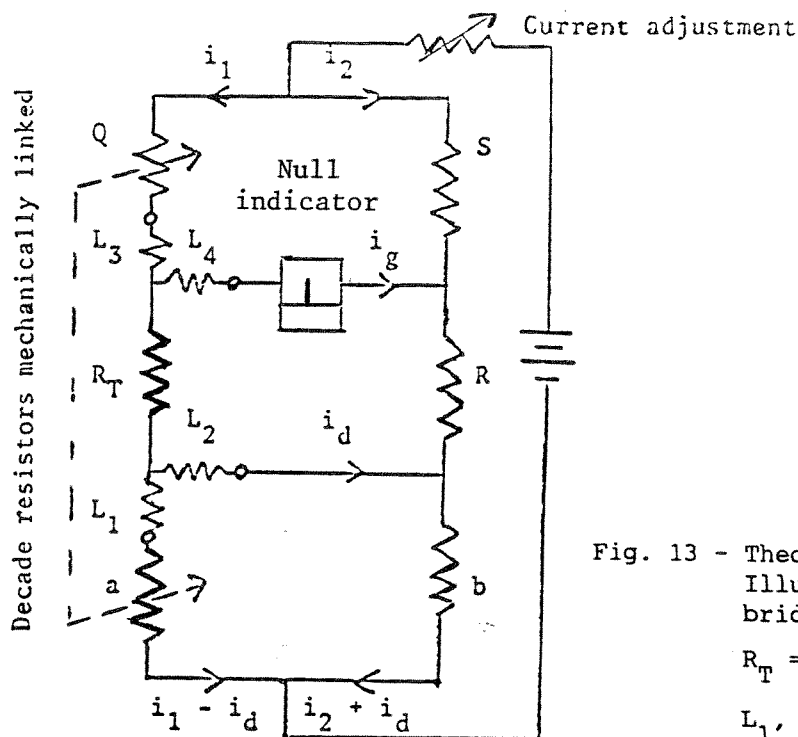


Fig. 13 - Theory of double bridges
Illustration shows Smith
bridge type III

R_T = Four-terminal resistance
thermometer
 L_1, L_2, L_3 and L_4 = Lead resis-
tances of the thermometer

At balance:

$$\begin{aligned} i_g &= 0 \\ i_1 R_T + i_d L_2 &= i_2 R \\ i_1 (Q + L_3) &= i_2 S \\ (i_1 - i_d)(L_1 + a) &= i_d L_2 + (i_2 + i_d)b \end{aligned}$$

whereof we can deduce the design equation for all types of double bridges:

$$R_T = \frac{RQ}{S} + \frac{R}{S} \left[L_3 - \frac{L_2(aS - Qb + SL_1 - bL_3)}{R(a + b + L_1 + L_2)} \right]$$

According to Smith's proposal one makes $aS - Qb = (a+b)R$ and $b = S$ by construction of the bridge. In this case if L_1 and L_3 are close in value and $a+b \gg L_1 + L_2$ the above equation reduces to¹

$$R_T = \frac{RQ}{S} + \frac{R}{S}(L_3 - L_2) \quad \text{according to Smith.}$$

In order to simplify the construction Gautier has proposed to make

$$\begin{aligned} a &= R' + Q' \quad \text{where } R' = R \text{ is fixed and } Q' = Q \text{ is variable} \\ b &= S - R \end{aligned}$$

$$R_T = \frac{RQ}{S} + \frac{R}{S}(L_3 - L_2) - \frac{R}{S} \cdot \frac{L_2 L_3}{Q' + S + L_1 + L_2} \quad \text{according to Gautier.}$$

The last term can be neglected in all practical applications as L_2 and L_3 are low compared to S . Usually one makes

$$\frac{R}{S} = \frac{1}{100} \text{ or smaller.}$$

- References: Smith F.E. - On Bridge Methods for Resistance Measurements of High Precision in Platinum Thermometry. Philosophical Magazine Vol. 24(1912). p. 541 - 569
- Gautier M. - A modification of the Smith bridge type 3. Journal of Scientific Instruments Vol. 30, Oct 1953 p. 381-382

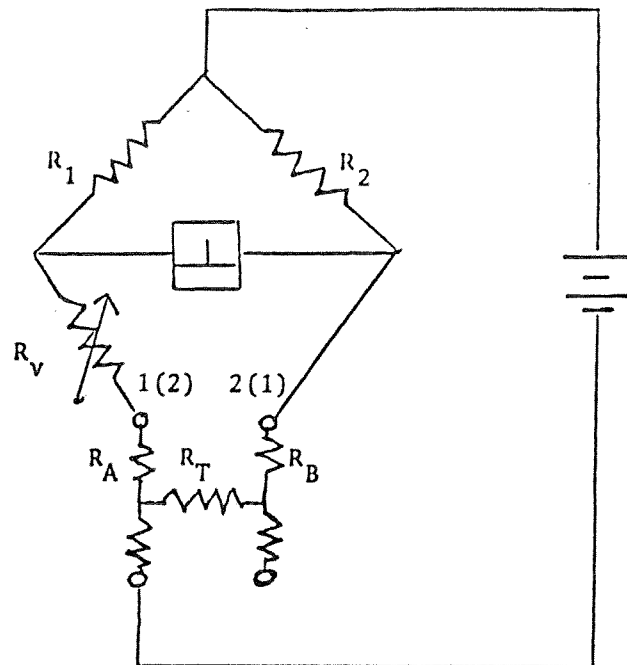


Fig. 14 - Mueller-bridge(uses reversal of R_T , two readings on R_V)

position 1-2 : $R_T + R_B = R_V + R_A$ if $R_1=R_2$ exactly

position 2-1 : $R_T + R_A = R'_V + R_B$

$$R_T = \frac{R_V + R'_V}{2}$$

Can be used as three-wire bridge without reversal of R_T if lead resistors R_A and R_B are practically equal:

$$R_T = R_V + R_A - R_B$$

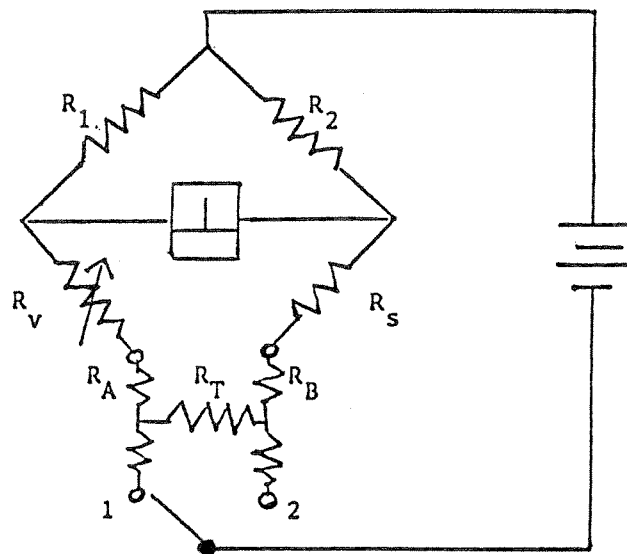


Fig. 15 - Difference bridge

position 1 : $R_V + R_A = R_T + R_B + R_S$ if $R_1=R_2$ and $R_S \geq R_T$

position 2 : $R'_V + R_A + R_T = R_B + R_S$

$$R_T = \frac{R_V - R'_V}{2}$$

Note that the thermometer R_T remains in this design in a fixed position and is therefore unaffected by variations in the switch contact resistance. Special switches have to be used with the Mueller bridge.

Resistance measurements with industrial platinum resistance sensors can be done by a Wheatstone bridge similar to the Mueller-bridge but with a fixed location of the resistance thermometer as explained in Fig. 14. In this case only three leads are required to the thermometer, the bridge arrangement is therefore usually called a three-wire bridge. Note that R_1 and R_2 in this bridge have to be of identical value and are usually provided with trimming facilities so as to render them equal through a reversal procedure. Some manufacturers supply special bridges which are suitable for four-lead connection to industrial sensors.

In the laboratory it is usually easy to construct a fairly accurate temperature indicating device if a sensitive potentiometer recorder or digital voltmeter is available as well as a stable adjustable voltage supply. The resistance sensor has to be equipped with two extra leads so as to constitute a four-lead resistor and connected in the same way as shown in Fig. 13 but by replacing the resistors Q , S , a and b by four fixed resistors of value $R_H = 10\ 000$ ohm and R by a temperature insensitive resistor of 100 ohm (supposing $R_0 = 100$ ohm of the sensor). The potentiometer recorder or the digital voltmeter is inserted at the location of the null indicator in Fig. 13. The bridge is directly connected to a stabilized DC voltage supply which is adjusted to 20 or 10 V depending on the maximum current allowed in the sensor taking into account self-heating effects (usually maximum 1 mA). The resistor R should have an adjustment facility so that the bridge can be set to zero when the sensor is dipped in a melting ice solution. The voltage indicated by the potentiometer compensating recorder will then be about 40 mV at $t = 100$ °C if the thermometer current is 1 mA, i.e. the supply voltage is $U = 20$ V. The indication will only be linear within a limited range but can easily be calibrated. The following approximate equation is obtained for this set-up:

$$U_m = \frac{U R_t}{2 R_H} \left(1 - \frac{R_t}{2R_H}\right) - \frac{UR}{2R_H} \left(1 - \frac{R}{2R_H}\right)$$

The latter term is constant and compensates for the voltage drop produced by the ice resistance R_0 of the sensor. The influence of variations on resistance of the leads is reduced approximately in the proportion $R_0/2R_s$, i.e. 100/20 000.

It is also possible to make temperature difference measurements with a resolution of 0.01 °C using this circuit whereby R is replaced by a second sensor of identical characteristics and the zero setting is made by slightly adjusting the resistors R_H .

V. RADIATION PYROMETRY

V.1. Black body conditions

The heat radiation from a surface depends on its radiation properties and on its temperature. The radiation from a black (or "grey") surface follows Planck's law for radiation, see Fig. 16. If the spectral distribution of the radiation does not follow this law it is still possible to use radiation receivers for the measurement of temperature variations but this requires that calibration takes place by other methods.

A surface which is located in a hollow body, is hit by radiation from the other surfaces of the walls. If the surface has the same temperature as the walls the result will be an exchange of radiation through emission and reflexion so that the surface will behave like a black body even if the properties of the surface are such that the emission of radiation in free space does not follow Planck's law.

Correct temperature measurements using Planck's law can thus be made in materials which otherwise do not follow this law if the measurements take place in a hole of the material which should have a depth of 10 times the diameter.

V.2. Emissivity factor ϵ

Radiation receivers which are calibrated for black body conditions can be used for measurement of temperature on free surfaces provided the mean emissivity factor is known for the band of wavelengths for which the radiation receiver is sensitive.

The influence of the emissivity factor on the temperature indicated is very different depending on the type of construction of the radiation receiver. The influence of the emissivity factor is lowest for radiation receivers which operate within a narrow band of wavelengths close to shortest wavelengths of the radiation spectrum. The correction to be applied for various factors of emissivity for common types of disappearing filament optical pyrometers is shown in Fig. 17. These pyrometers operate with an effective maximum at the wavelength $0.655\mu\text{m}$ which is located in the red part of the visual spectrum. Some approximate values for the emissivity factor are given below:

material	narrow band radiation with maximum at $0.655\mu\text{m}$	
	polished surface	oxidized surface
copper	0.10 - 0.15	0.7
steel	0.35	0.8
cast iron	0.4	0.7
ceramics (china)	0.25 - 0.5	
aluminium oxide	0.2 - 0.3	
carbon, graphite	0.8 - 0.9	

radiated energy

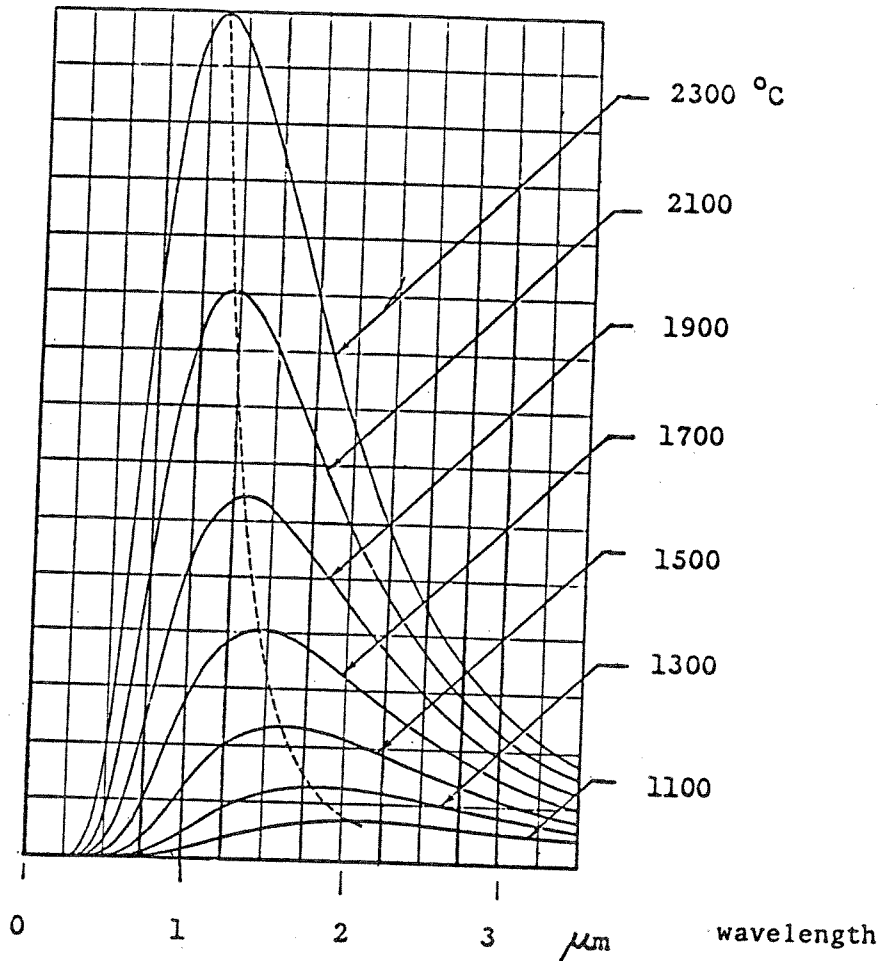


Fig. 16 - Relative spectral distribution of radiated energy for a "black" radiator according to Planck's law

Emissivity ϵ_λ	CORRECTIONS °C															
0.9	5	6	7	8	9	10	12	13	15	17	19	21	23	25	27	30
0.8	10	12	14	17	19	22	25	29	32	36	40	45	49	54	58	64
0.7	16	19	23	27	31	36	41	47	53	59	65	72	79	87	95	103
0.6	23	27	33	39	45	52	60	68	76	85	95	105	116	127	138	151
0.5	31	38	45	53	62	72	82	93	105	117	131	145	160	175	192	209
0.4	40	50	60	70	80	100	110	125	140	160	180	200	220	240	260	280
0.3	55	65	80	95	110	130	150	170	190	215	240	265	300	320	350	390
0.2	75	90	110	130	150	180	205	230	260	300	330	370	410	450	500	550
0.1	110	140	165	195	230	270	310	355	400	460	515	575	640	710	780	865
	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200

Temperature indicated °C

Fig. 17 - Computed corrections for various coefficients of emissivity at $\lambda = 0.655 \mu\text{m}$ to be added to the indication of a disappearing filament pyrometer operating at the same average wavelength. (As it is difficult to know exact values of the emissivity coefficient meaningful corrections can usually only be applied when $\epsilon \geq 0.5$).

As a general rule one can apply radiation pyrometry on free surfaces provided the emissivity factor is higher than 0.5 and applying the necessary corrections found from estimates or experience.

V.3 Influence of parasitic reflexions on free surfaces

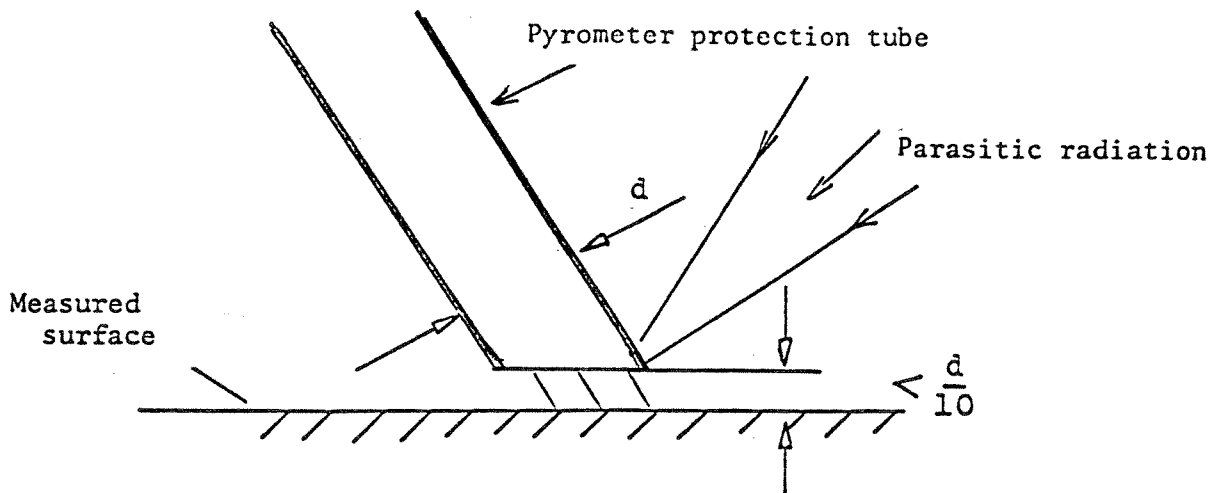
If the emissivity factor is low one must take special precautions so as to avoid parasitic reflexions on the surface measured from other sources of radiation, in particular when working with low-temperature infra-red sensitive pyrometers. A non-transparent surface with an emissivity factor of $\epsilon = 0.1$ has a reflectivity factor $r = 1 - 0.1 = 0.9$, i.e. 90 % of the received radiation is reflected towards the radiation receiver. This makes it practically impossible to control directly through radiation pyrometry the temperature of aluminium melts. For certain other materials it is possible to choose a receiver which is sensitive only for a particular wave-length band where the absorption of radiation of the material is high and consequently the emissivity factor high. For glass melts the best wave-length region is from 4.5 to 8 μm and can be measured with some types of infra-red receivers equipped with suitable filters to eliminate radiations of lower wave-length.

Even in cases where only variations in temperature have to be detected it is necessary to avoid parasitic reflexions from other sources such as furnace walls etc. This can sometimes be done geometrically by using screens or protection tubes which are located close to the surface to be measured, see Fig.18.

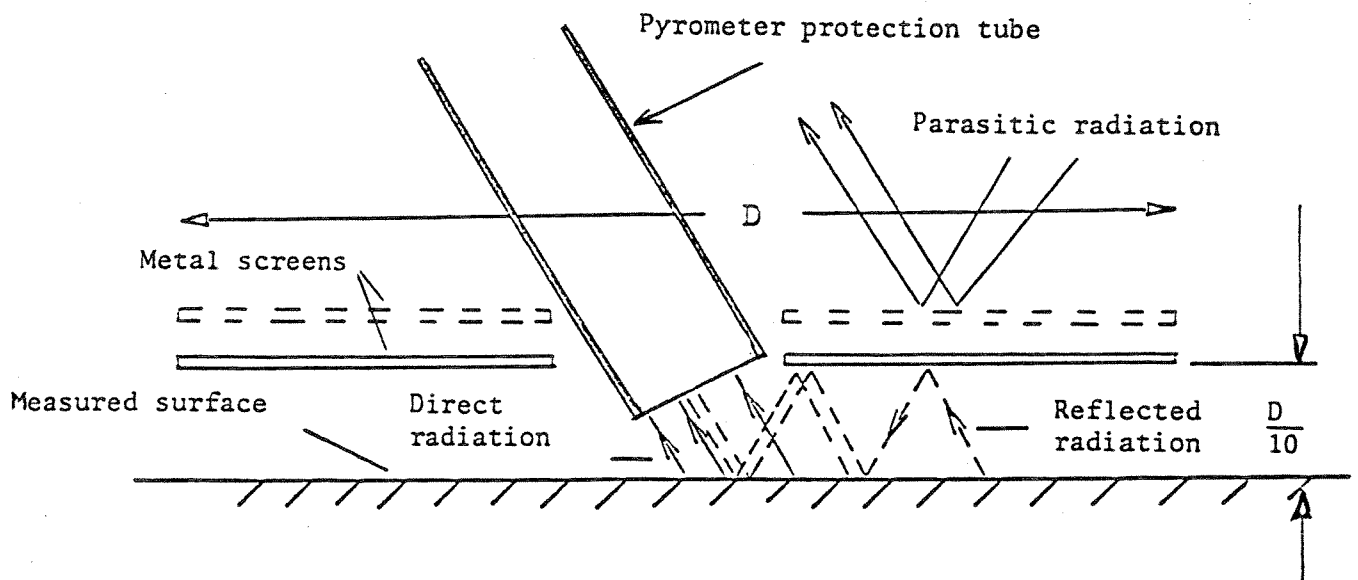
V.4 Types of radiation pyrometers

One may distinguish between essentially four types of radiation pyrometers with regard to the wave-length band for which they are sensitive:

- spectral pyrometer - a pyrometer which uses a narrow wave-length band. (The disappearing filament pyrometer Fig. 19 approaches this condition)
- partial radiation pyrometer - uses a large wave-length band limited by the sensitivity of the detector, filters, optics etc
- total radiation pyrometer - uses a very large wave-length band (preferably infinite) which is limited however by optics, protection glass, etc
- ratio radiation pyrometer - measures the ratio of radiations received within (or two-colour pyrometer) two separate wave-length bands



Protection against parasitic radiation without use of special screen and without increase of coefficient of emissivity



Protection against parasitic radiation using one or several metal screens and increase of coefficient of emissivity by multiple reflexions

Fig. 18 - Means of avoiding influence of parasitic radiation in radiation pyrometry

V.5 The disappearing filament optical pyrometer Fig. 19.

The disappearing filament pyrometer uses a very narrow band-width of wavelengths usually located with a maximum at $0.655 \mu\text{m}$. The luminance of the sighted surface is in this pyrometer compared with the luminance of a tungsten filament contained in a small lamp. The current through the filament is adjusted until there is no visual difference in luminance between that of the surface sighted and that of the filament. The current of the pyrometer lamp is calibrated as a function of temperature. In some types of construction the filament current is kept constant and measurements made by adjusting the luminance through an optical device containing a grey wedge, i.e. a neutral filter with variable optical transmission.

The calibration of disappearing filament optical pyrometers is made by using specially calibrated tungsten ribbon lamps which have been compared to a black body radiator, usually at the freezing point of gold. As the filament in the disappearing filament pyrometer becomes thinner through evaporation when frequently used, it is necessary to recalibrate these instruments at regular intervals.

V.6 Total radiation and partial radiation pyrometers

The disappearing filament pyrometer is practically the only accurate optical temperature measuring device of all other types of receivers. It is however generally not suitable for continuous temperature measurements or process control for which one uses other types of radiation receivers such as thermopiles (total radiation type) or silicium photocells, etc.

At low temperatures, below 1000°C it is required that the detector with its optics is sensitive in the long-wave infra-red region of the spectrum. Thermopiles are frequently used equipped with suitable non-absorbing optics such as mirrors, lenses made from quartz or calciumchloride etc. At higher temperatures, over 1000°C it is possible to use receivers which are sensitive in the short-wave region of the infra-red spectrum and the optics can be made from usual glass. Silicium photocells (so-called solar cells) are frequently used in this case. Their wave-length limit to the long wave region of the spectrum is $\lambda_{\text{max}} = 1.2 \mu\text{m}$ which has the advantage of reducing the influence of variation in emissivity factor on the measurements. When choosing the type of radiation pyrometer it is however absolutely necessary to check that the emissivity factor within the sensitive band-width of the detector is at least 0.5 for the materials to be measured or controlled in order to avoid influence from other sources of radiation.

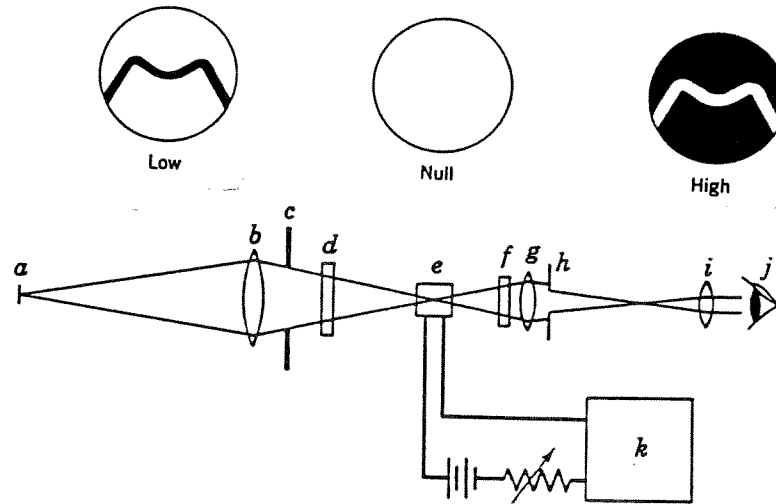


Fig. 19 - Schematic diagram of an optical pyrometer: (a) source; (b) objective lens; (c) objective aperture; (d) absorption filter (used for temperatures above 1300°C); (e) pyrometer lamp; (f) red filter; (g) microscope objective lens; (h) microscope aperture stop; (i) microscope ocular; (j) eye; (k) current measuring instrument. (After NBS Monograph 41.)

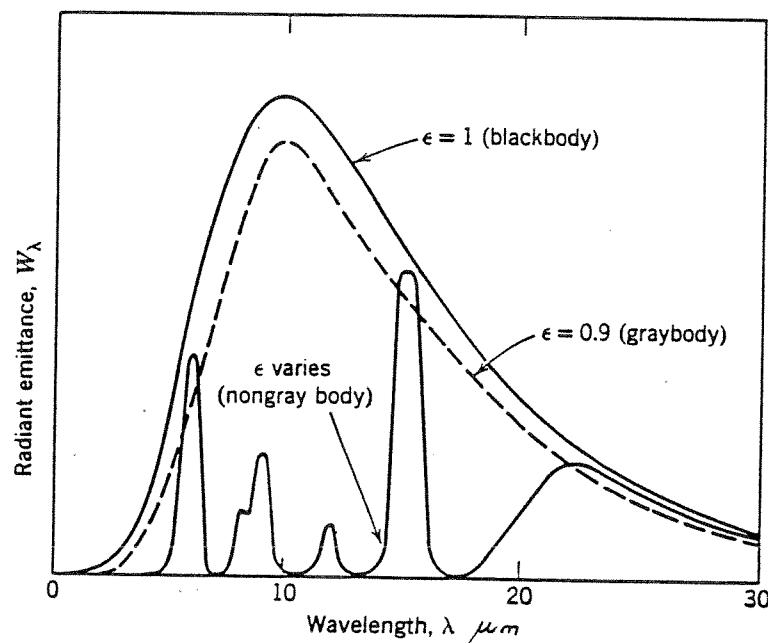


Fig. 20 - Emitted radiation as a function of emissivity for bodies at 300 K. (After King et al. 1963.)

The calibration of total radiation or partial radiation pyrometers can be done in the laboratory by using a tube furnace constructed so as to imitate a black body radiator. The temperature can be determined in this case by a standard platinum-platinum 10%-rhodium thermocouple (up to 1300 °C). These calibrations will however generally not allow accurate temperature measurements with total radiation pyrometers in industrial applications but may be used to determine the reproducibility with time of the radiation detectors. The latter are often badly exposed to fumes, heat and dust on optical surfaces. They are compensated for variations in ambient temperature but this compensation is not operative if the temperature of the housing in the factual installation is too high. The reproducibility of the readings of a total radiation receiver can be controlled regularly on its installation site if provisions are made for the simultaneous but temporary use of a disappearing filament pyrometer. Exact determination of the temperature of molten metals and other liquids at high temperature is difficult but can sometimes be done using special thermocouples which are frequently exchanged (dip thermometry).

V.7 Ratio measuring radiation pyrometers (two-colour pyrometers)

This type of pyrometer is based on the fact that the steepness of the Planck curve in the short-wave region of the spectrum is a measure of the temperature. The radiation received within two separate narrow bands of the spectrum is thus measured and the ratio is established through the use of electrical circuitry. This type of pyrometer is in its principle insensitive to variations in emissivity factor provided the latter varies with the same relative amount at the two wave-lengths for which the receiver is sensitive, i.e. the radiating surface behaves like a grey body (see Fig.20). This is however frequently not the case. For molten copper or gold the emissivity factor is $\epsilon = 0.6$ at $\lambda_1 = 0.5 \mu\text{m}$ but only $\epsilon = 0.2$ at $\lambda_2 = 0.65 \mu\text{m}$, i.e. the variation is 300 %. For molten steel or cast iron it is found that the emissivity factor varies only slightly in this region of the spectrum but this is practically an exception.

This type of instrument is less sensitive to screening-off effects of the measured surface provided sufficient sensitivity is still available. It is however frequently more sensitive to parasitic reflexions from other radiation sources than other pyrometers.

In conclusion one may say that ratio measuring (or two-colour) pyrometers may, if they do not contain very delicate electronics, be used for temperature measurements of molten steel or similar surfaces with "grey" radiation characteristics.

LITERATURE

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