WMO Online Training Workshop on Quality, Traceability and Compliance – General Metrology and Temperature, for RICs and RMICs

WEATHER CLIMATE WATER
TEMPS CLIMAT EAU

Temperature Measurements

Calibration of thermometers by Comparison

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World Meteorological Organization
Organisation météorologique mondiale

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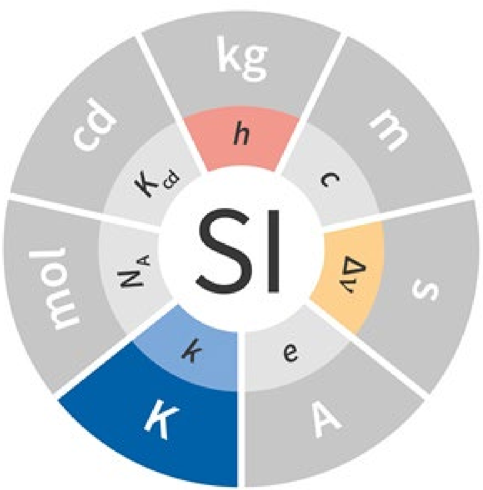
Definitions. Unit of temperature

The Unit of Temperature in the International System of Units is the kelvin (K)

The current definition of the kelvin was agreed by the 26th CGPM (November 2018) and came into force the 20th May 2019 [(1)]:

> The kelvin, symbol K, is the SI unit of thermodynamic temperature (T). It is defined by taking the fixed numerical value of the Boltzmann constant k to be 1.380 649 x 10^{-23} when expressed in the unit J K^{-1}, which is equal to   kg m^2 s^{-2} K^{-1}, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$.



This definition implies the exact relation k = 1.380 649 x 10^{-23} kg m^2 s^{-2} K^{-1}. Inverting this relation gives an exact expression for the kelvin in terms of the defining constants k, h and $\Delta\nu_{Cs}$:

$$1\,\mathrm{K} = \left(\frac{1.380\,649}{k}\right) \times 10^{-23}\ \mathrm{kg\,m^2\,s^{-2}}$$

The effect of this definition is that one kelvin is equal to the change of thermodynamic temperature that results in a change of thermal energy $k\,T$ by 1.380 649 x 10^{-23} J.

(1) www.bipm.org

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Definitions. Unit of temperature

By this new definition, the unit of temperature is related to a **universal constant**:

- avoiding its dependence from any material properties;
- it does not imply any particular method or experiment for its practical realization;
- the purpose of this new definition is to lay the foundations for future improvements by making the kelvin independent of any material element, measurement technique or temperature range in agreement with the overall definition of the seven base units of the SI.

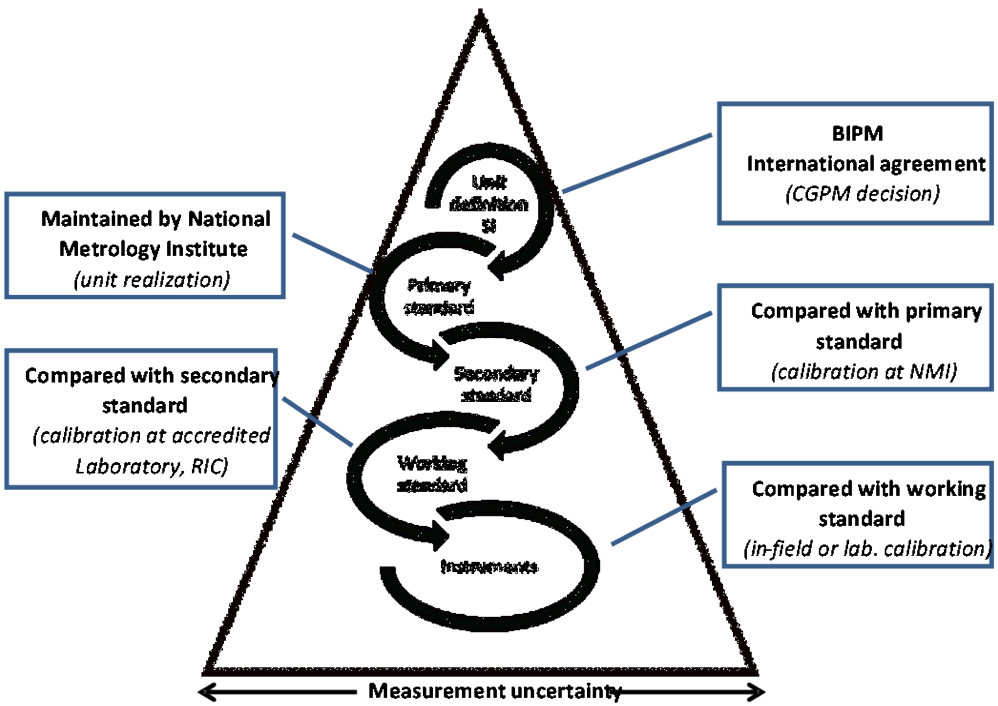
Although the kelvin redefinition fundamentally modifies the principles and practices of thermometry,

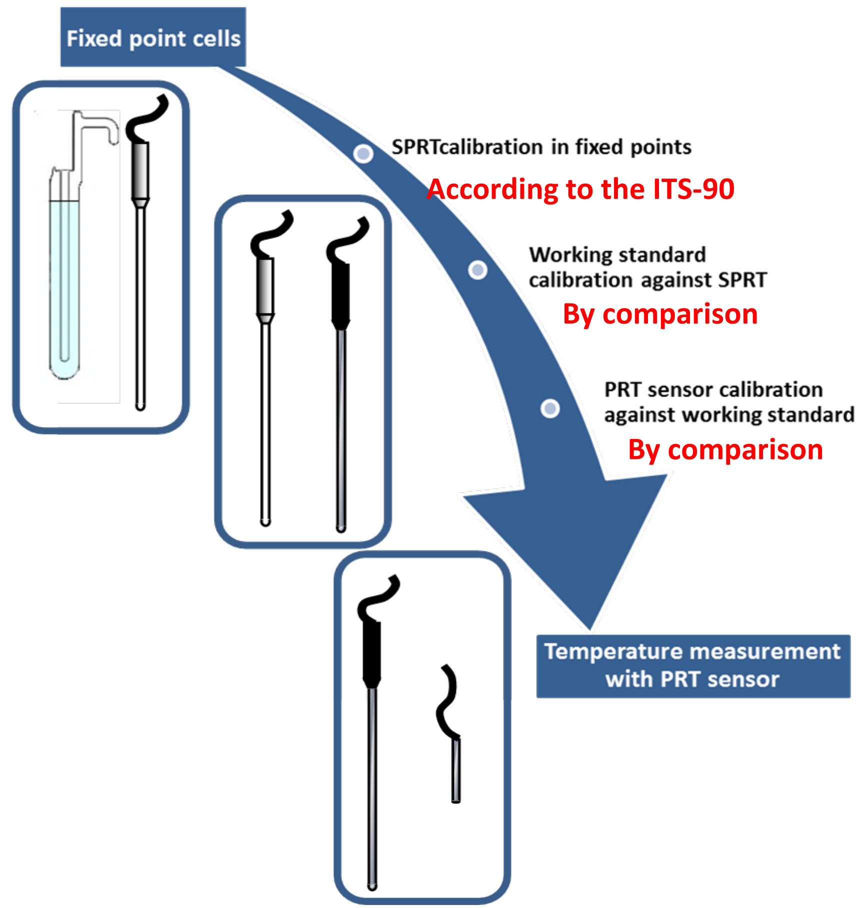
- in the short term very little will change from the point of view of the most end users.
- The status and contents of the International Temperature Scale of 1990 (ITS-90) remains unchanged.
- The temperature calibrations performed according to ITS-90 will be valid and traceable to the SI.

The unit of Celsius temperature (t) is the degree Celsius, symbol °C, which is by definition equal in magnitude to the unit kelvin; both are units of the SI.

$$t/°\mathrm{C} = T/\mathrm{K} - 273.15$$

Definitions. Traceability chain in contact thermometry

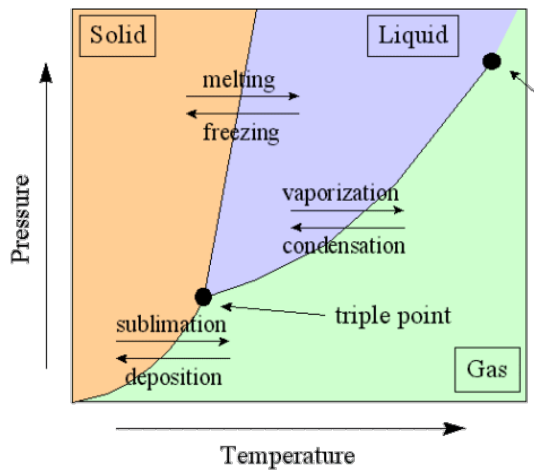




ITS-90. Calibration in fixed points

Melting and freezing plateaus

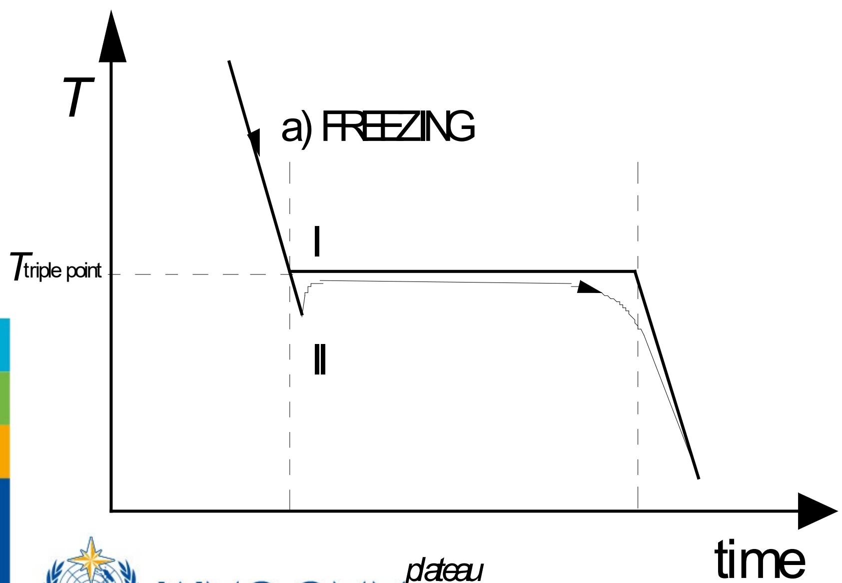
The fixed-point temperatures of the ITS-90 are defined for phase transitions (triple, melting, and freezing points) of ideally-pure, single-component substances

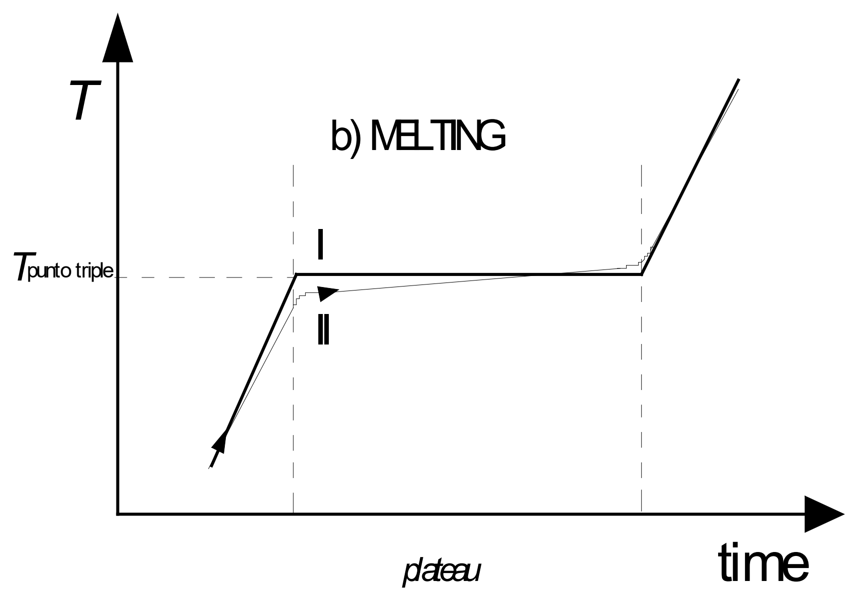


The phase transition plateaus are the period of time in which a substance experience a phase transition:

-From liquid to solid: freezing plateau

-From solid to liquid: melting plateau





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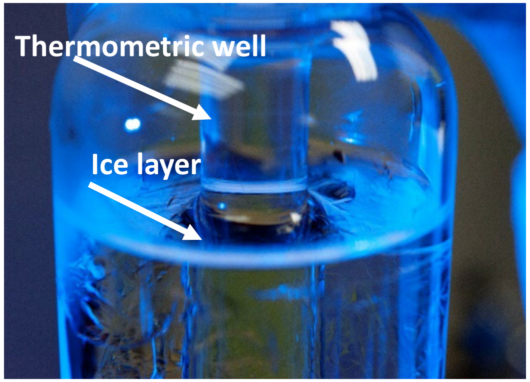
ITS-90. Calibration in fixed points

The Triple Point of Water:

- t_{90} = 0.01 ºC
- A triple point of water cell contains: ice, water and water vapour.

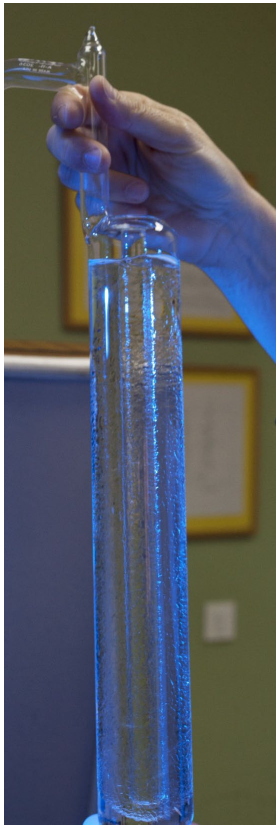
This is achieved with an ice mantle surrounding the thermometer well, with a thin water interface between the ice and the well.

- Stability of thermometers



Mercury fixed point:

- t_{90} = -38.834 4 ºC
- Triple point of Mercury
- Condition of the Thermometer to be interpolation instrument of the ITS-90: W (-38.834 4 ºC) ≤ 0.844 235



Gallium fixed point:

- t_{90} = 29.764 6 ºC
- Melting fixed point
- Usually used to check the contamination of the SPRT
- Condition of the Thermometer to be interpolation instrument of the ITS-90: W (29.764 6 ºC) ≥ 1.118 07

ITS-90. Fixed points

Metal Fixed Points

In most cases, the metal sample is contained in a high purity **graphite crucible**, being the thermometric well also made in graphite.

A volume of 100 ml to 250 ml is usually required. **An immersion** of the thermometer of at least 20 cm is needed for optimal realizations.

The graphite crucible is assembled in a **glass or quartz tube** (depending on the temperature), and a second thermometric well made of glass or quartz is also inserted in the graphite crucible.

In the case of the Ga cell, the crucibles are made of PFTE and Stainless Steel or glass is used for mercury.

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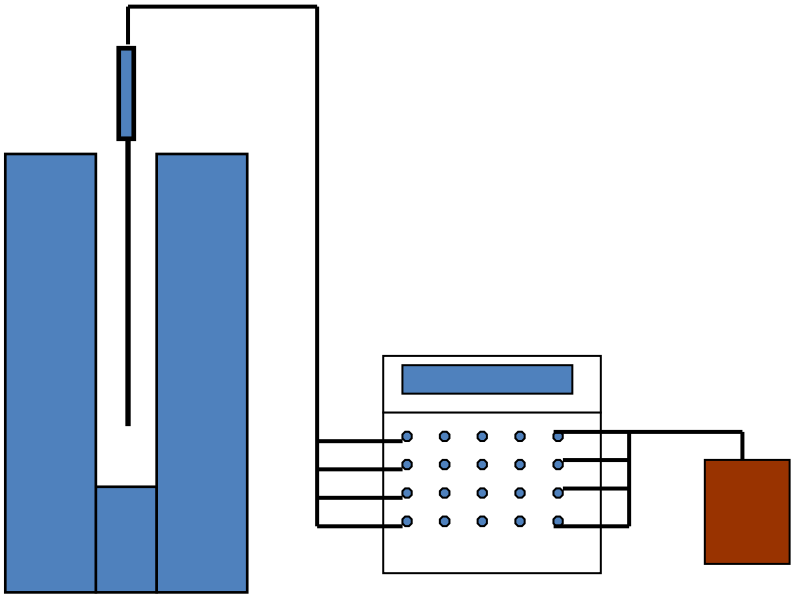
ITS-90. Calibration in fixed points



$L = R_{sprt}\,(T)/R_{\ standard}$

↓

$\boldsymbol{R_{TRPP}\,(T)}$

↓

$W(T) = R_{SPRT}(T)/R_{SPRT}(0.01\ ^{o}C)$

↓

$\boldsymbol{W_{SPRT}(T)}$

↓ ← $\boldsymbol{W_{ref}(T_{90})}$

Coefficients of the deviation equation:

Real behaviour of the thermometer

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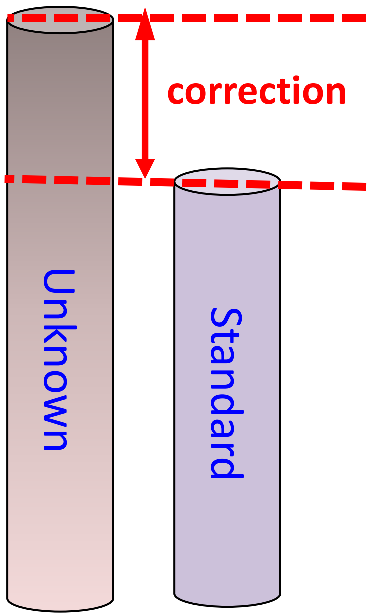
Calibration by Comparison

-Calibration [1] **:** operation that, under specified conditions, in a first step, establishes a relation between the **quantity values** with **measurement uncertainties** provided by **measurement standards** and corresponding **indications** with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a **measurement result** from an indication



-The Calibration by the Comparison Method in contact thermometry: the measurements of the thermometer under calibration are compared with the ones of standard thermometers (traceable to the ITS-90) in an isothermal enclosure. In general, 4 to 5 calibration points covering the calibration range are recommended.

Correction = value of Standard – reading of instrument under calibration

Error = - Correction

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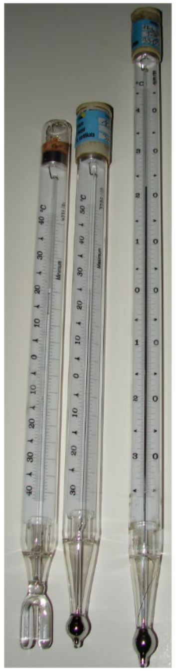
[1] International Vocabulary of Metrology, VIM. www.bipm.org

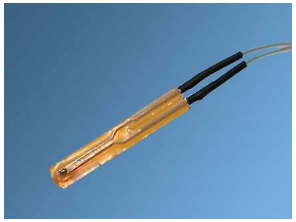
Types of contact thermometers

A thermometer is any device which has a measurable property which changes with temperature.

To have accurate measurements it is necessary to assure the thermal equilibrium of the thermometer and the measured object/system. In the case of contact thermometers, the equilibrium is reached mainly by heat conduction between the measured object /system and the thermometer.

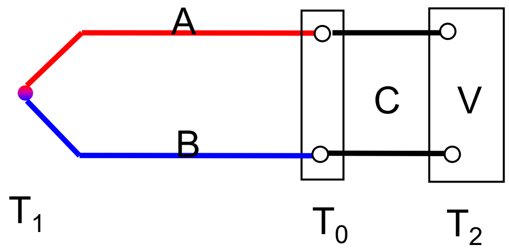


Liquid-in-glass thermometers:
Expansion of a fluid in a capillary stem with temperature

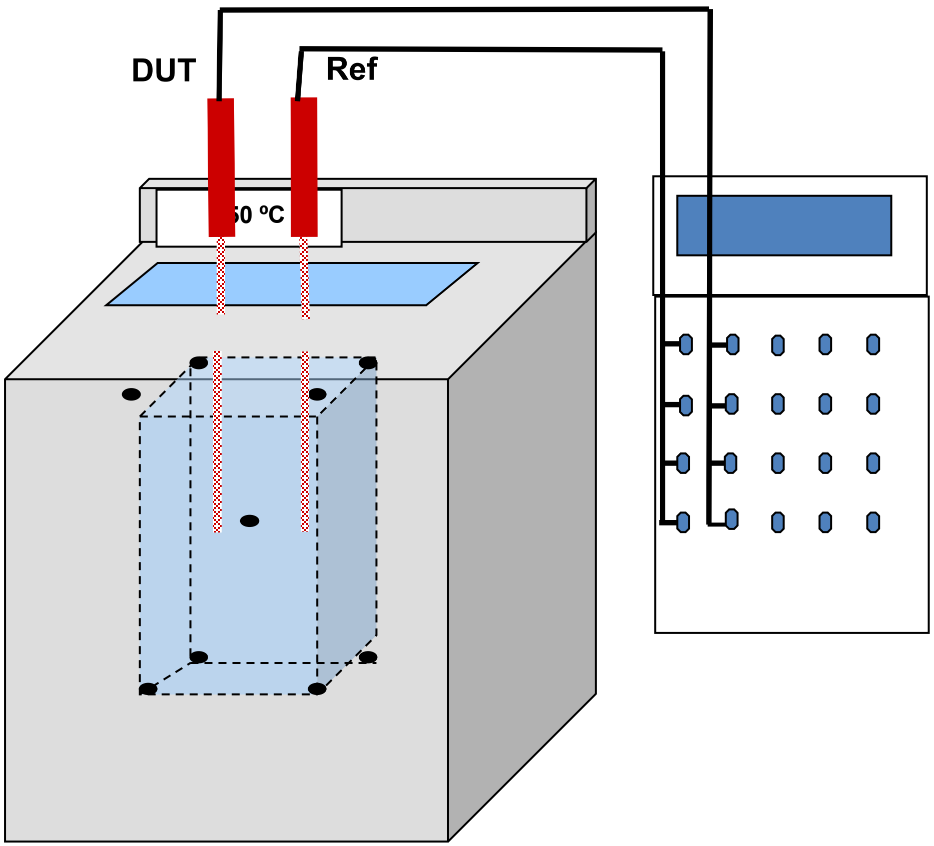


Platinum resistance thermometers and thermistors:
Change of electrical resistance of metals and semiconductors (thermistors) with temperature

Thermocouple:
Change of the electromotive force along two dissimilar electrical conductors, joined at one end with a temperature difference between their endpoints (Seebeck effect)



Calibration by Comparison. One reference thermometer



NEEDED EQUIPMENT :

- 1 standard thermometer
- Isothermal enclosure: Liquid bath, Climate chamber, etc.
- readout device (bridge, multimeter,…)

PREVIOUS REQUIREMENTS

- Calibration of the standard
- Thermal characterization of the isothermal enclosure (determination of its stability and spatial uniformity in temperature) :
- Determination of the **appropriate immersion depth** of the standard and the thermometer to be calibrated, to assure that there are no heat conduction errors.

Calibration by Comparison. One reference thermometer. Data treatment.

The case in which a platinum resistance thermometer is calibrated by comparison against one standard platinum resistance thermometer (Pt-100) is presented:

-The same resistance bridge is used to perform all the measurements (standard and thermometer to be calibrated).

-The reading of the resistance bridge is the ratio of the thermometer resistance to an electrical standard resistor ($R_{\text{bridge-standard}}$).

(*) In the case of the calibration of a thermometer with an indicator (**DIRECT Reading thermometer or Electronic thermometer**), the reading of the thermometer under calibration will be obtained directly in °C:

$$t_{c1}(t_{\text{ref}}) = I_{\,electronic\ thermometer}$$

1) Resistance bridge indications (readings): I_{S1} I_{C1} (*)

2) Thermometers resistance: $R_s = I_{s1} \cdot R_{\text{bridge-standard}}$ $\boldsymbol{R_{c1}} = I_{c1} \cdot R_{\text{bridge-standard}}$

3) Using the interpolation equation for each standard thermometers $\boldsymbol{t_{s1}} = f(R_s)$

(consult the calibration certificate):

4) The reference temperature of the calibration point is : $\boxed{t_{\text{ref}} = \boldsymbol{t_{s1}}}$

5) The reading of the thermometer under calibration: $\boxed{R_c(t_{\text{ref}}) = \boldsymbol{R_{c1}}}$

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Calibration by Comparison. One reference thermometer

The calibration measurements need to be performed under the conditions of **stability** and **uniformity** of the isothermal enclosure established in the calibration procedure (characterization of the isothermal enclosure).

The **stability** of the isothermal enclosure can be checked by the reading of the standard at each calibration point

The **uniformity**. Very important to be checked (specially in climate chamber). Significant contribution to the calibration uncertainty

In order to **assure the quality** of the measurements:

Two standards can be used:

1- To check the uniformity of the isothermal enclosure at each calibration point

2- For the early detection of potential problems, allowing:

- Continuous control of the standards drift.
- Continuous control of the isothermal enclosure performance
- Control of the quality of the liquids in the baths (in special when ethanol is used)

Calibration by Comparison. Two reference thermometers

NEEDED EQUIPMENT :

- 2 standard thermometers
- Isothermal enclosure: Liquid bath, Climate chamber, etc.
- readout device (bridge, multimeter,…)

PREVIOUS REQUIREMENTS

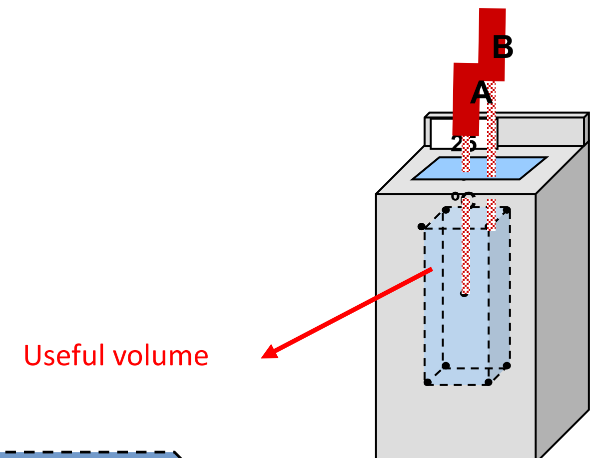
- Calibration of the standards

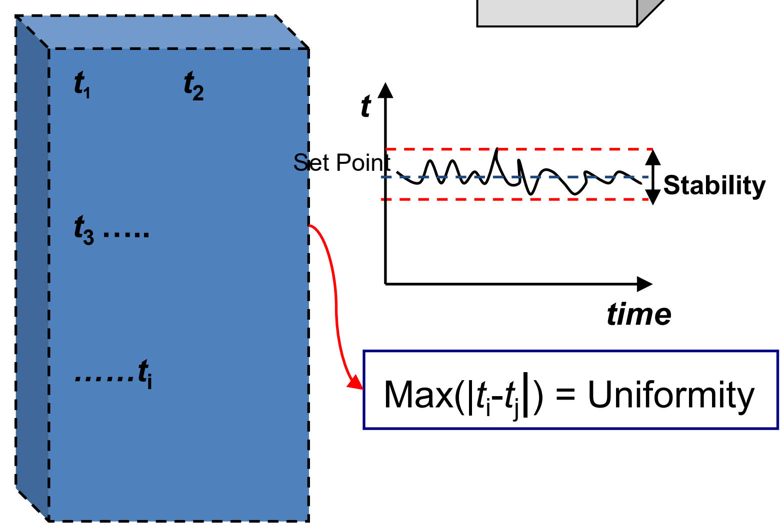
- Thermal characterization of the isothermal enclosure (determination of its stability and spatial uniformity in temperature) :

-**Isothermal enclosure stability**: maximum temperature variation of the isothermal enclosure in a determined period of time.

-**Isothermal enclosure spatial uniformity**: maximum temperature variation of the isothermal enclosure in the volume used for calibration, currently known as useful volume.

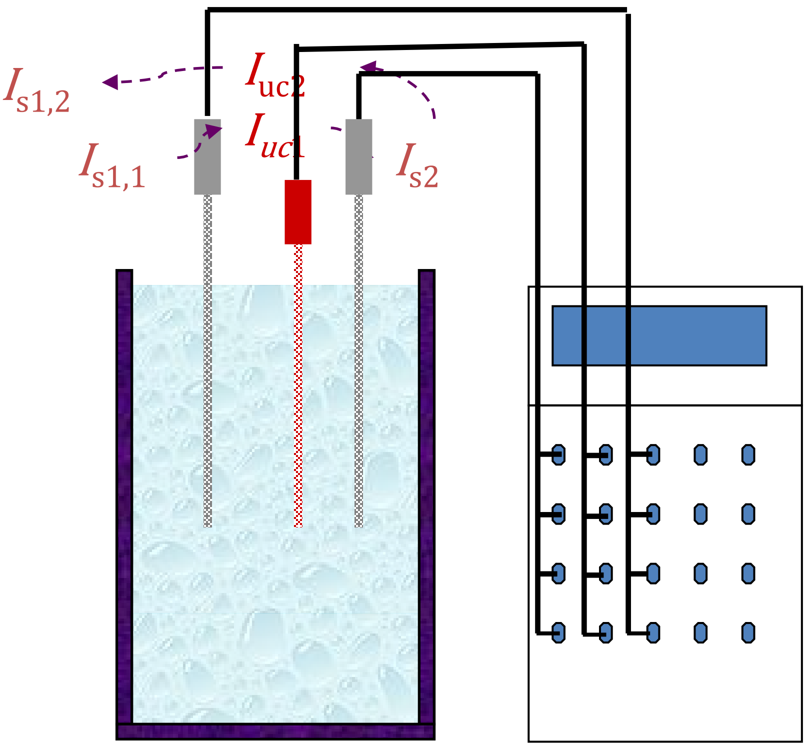
-Determination of the **appropriate immersion depth** of the standards and the thermometer to be calibrated, to assure that there are no heat conduction errors.





Calibration by Comparison. Two reference thermometers.

Data acquisition.

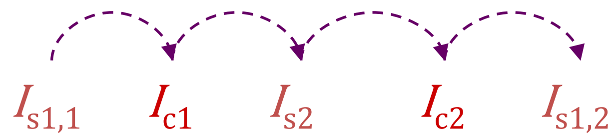


standard thermometers

thermometer under calibration

Thermometers reading system:
-it can be the same for all thermometers, in case the calibration of resistance thermometers,
-The thermometer under calibration can have its own reading system (electronic thermometers: sensor + indicator

Reading cycle for each calibration point:



The use of two standards and this reading cycle allows to check the stability and uniformity in temperature of the isothermal enclosure in each calibration point by using the readings the standards:

Stability check:

$I_{s1,1} - I_{s1,2}$ < stability of isothermal enclosure (previously determined)

Uniformity check:

$(I_{s2} - (I_{s1,1} + I_{s1,2})/2)$ < uniformity of isothermal enclosure (previously determined)

These checks allow a better assurance of the calibration quality.

Calibration by Comparison. Two reference thermometers. Data treatment.

The case in which a platinum resistance thermometer is calibrated by comparison against two standard platinum resistance thermometers (eq. SPRT 25) is presented. It is supposed that the same resistance bridge is used to perform all the measurements. The reading of the resistance bridge is the ratio of the thermometer resistance to an electrical standard resistor ($R_{\text{bridge-standard}}$).

1) Resistance bridge indications (readings): I_{S1} → I_{C1} (*) → I_{S2} → I_{C2} (*) → $I_{S1,2}$

2) Thermometers resistance:

$R_{s1} = I_{s1} \cdot R_{\text{bridge-standard}}$

$\boldsymbol{R_{c1}} = I_{c1} \cdot R_{\text{bridge-standard}}$

$R_{s2} = I_{s2} \cdot R_{\text{bridge-standard}}$

$\boldsymbol{R_{c2}} = I_{c2} \cdot R_{\text{bridge-standard}}$

$R_{s1,2} = I_{s1,2} \cdot R_{\text{bridge-standard}}$

3) Using the interpolation equation for each standard thermometers (consult the calibration certificate):

$\boldsymbol{t_{s1,1}} = f(R_{s1})$

$\boldsymbol{t_{s2}} = g(R_{s2})$

$\boldsymbol{t_{s1,2}} = f(R_{s1,2})$

4) The reference temperature of the calibration point is :

$$\boxed{t_{\text{ref}} = \frac{\frac{t_{s1,1} + t_{s1,2}}{2} + t_{s2}}{2}}$$

5) The reading of the thermometer under calibration:

$$\boxed{R_c(t_{\text{ref}}) = \frac{R_{c1} + R_{c2}}{2}}$$

(*) In the case of the calibration of a thermometer with an indicator, the reading of the thermometer under calibration will be obtained directly in °C:

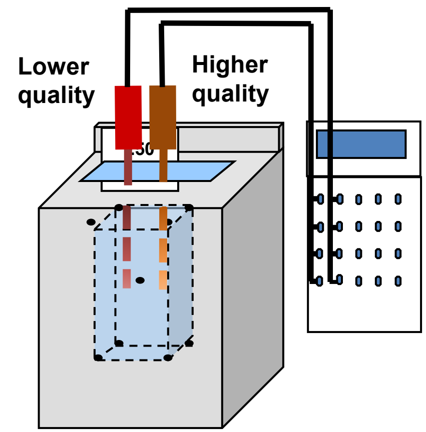
$$t_c(t_{\text{ref}}) = \frac{I_{c1} + I_{c2}}{2}$$

Calibration by Comparison. Two reference thermometers. Other configurations

- **Two standards of different quality**:
- difference between the two thermometers: check of isothermal enclosure uniformity
- Calibration temperature /reference thermometer:

  Given by ONE thermometer, the one with highest quality:

$$t_{\text{ref}} = \boldsymbol{t_{s1}}$$

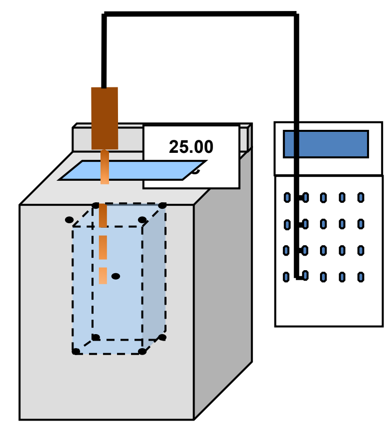


- **Indication of isothermal enclosure as the second standard**:
- Only possible if the display has enough resolution regarding the expected uniformity
- Only possible if the isothermal enclosure is calibrated:

The corrections of the display indications were determined in a previous calibration of the isothermal enclosure

- Difference between the reading of the standard and the corrected display value: check of the isothermal enclosure uniformity
- The reference temperature is given by the standard:

$$t_{\text{ref}} = \boldsymbol{t_{s1}}$$



Calibration by Comparison. Additional tests.

Depending of the type of sensor under calibration, specific sources of uncertainty should be investigated by performing additional tests:

Resistance thermometers

- Hysteresis and/or repeatability (platinum resistance thermometers and thermistors)
- Self-heating (platinum resistance thermometers)

Thermocouples

- Thermoelectric inhomogeneity

Liquid-in-glass thermometers

- Hysteresis or depression of zero

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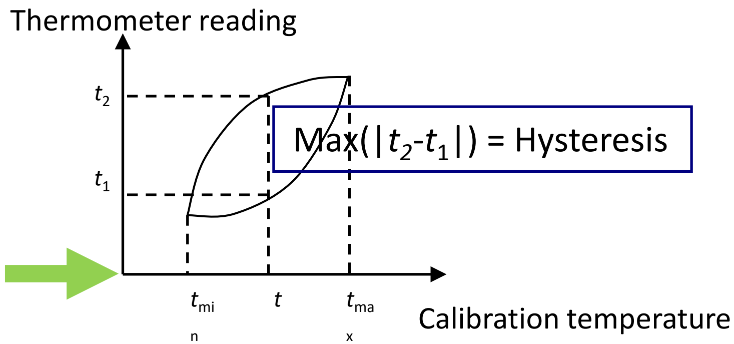
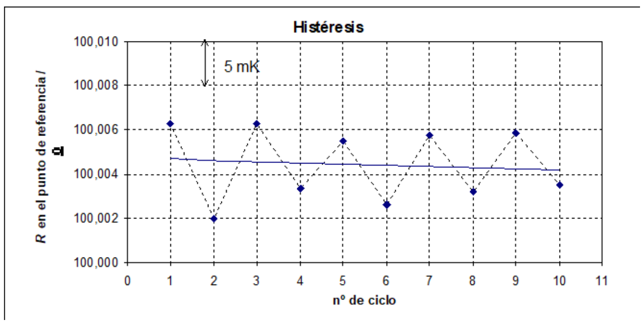
Calibration by Comparison. Additional tests.

Hysteresis: is the dependence of the temperature-resistance relationship of a thermometer on its previous history. This can result in a difference in the thermometer indication up to several tenths of a degree according to whether the thermometer was used at higher or lower temperatures.





If the thermometer calibration range is wide, the hysteresis effect can be significant.

For accurate calibration: several heating-cooling cycles between the max and min calibration temperatures, with determination of thermometer reading at an intermediate temperature can be performed.

For less accurate calibrations: One cycle is performed. Hysteresis: the maximum difference between two readings. It can be consider as a maximum limit for this source of uncertainty.

If the calibration temperature range is around ambient temperature the hysteresis effect could be almost negligible and this test could be replace by a simple repeatability test in one of the calibration points.

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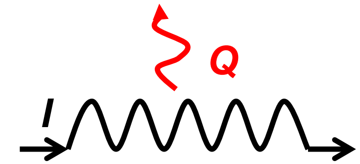
Calibration by Comparison. Additional tests.

Self-heating: caused by the Joule effect; the passage of the measurement electrical current through the sensing element of the resistance thermometer produces heat.



This source of uncertainty could be significant if the calibration conditions differ from those of use.

The influence of the self-heating can be evaluated by measuring the variation of thermometer resistance with the measuring current. Commonly, at 1 mA and √2 mA.

$$\left(R_{\sqrt{2}\cdot I} - R_I\right) = Self - heating$$

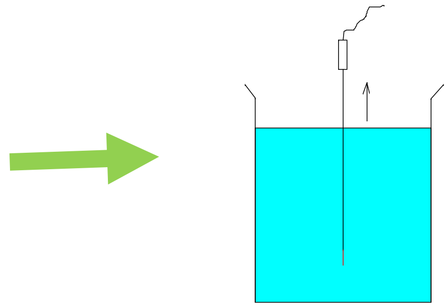
These values can also be plotted as a function of I^2, and extrapolated linearly to 0 mA which gives a resistance value free from self-heating effects.

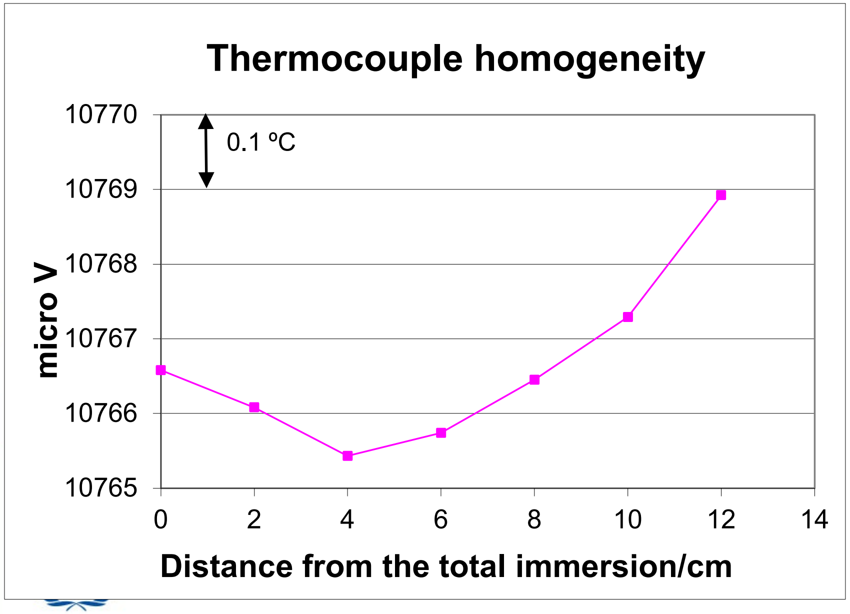
Calibration by Comparison. Additional tests.

Thermoelectric inhomogeneity: Thermoelectric inhomogeneity causes the dependency of the thermocouple reading with the temperature gradients.

the thermoelectric inhomogeneities causes systematic errors and limit the measurement uncertainty.

Thermoelectric inhomogeneity can be quantified by moving the measuring junction in an environment with homogenous temperature distribution (e.g. a stirred liquid bath or a fixed point cell, or specialized single gradient scanner).





$\boxed{\mathrm{Max}(|V_2\text{-}V_1|) = \mathrm{Homogeneity}.}$

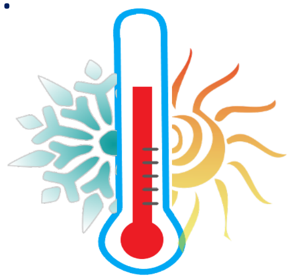
The largest emf difference found during the test should be taken as half width of a rectangular distribution

Rectangular distribution

$$u(\delta t_{homogeneity})= \frac{0.4}{\sqrt{12}} \sim 0.115\ °\mathrm{C}$$

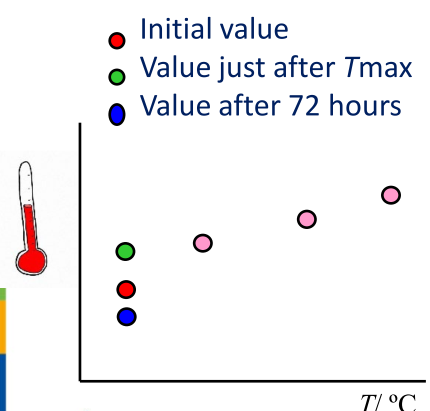
Calibration by Comparison. Additional tests. Hysteresis or depression of zero/Liquid in glass thermometers.

Hysteresis or depression of zero: Thermometric glasses exhibit simple hysteresis characteristics. Once heated, glass fails to return quickly to its original size. Recovery from this condition may not be complete for several hours or even days. In consequence this effect imposes some limitations, since once a liquid-in-glass thermometer is used at a high temperature it cannot be used at lower temperature until the bulb has been allowed to recover.



Hysteresis or depression of zero can be quantified by measuring the thermometer reading at:

- the minimum temperature at the beginning of the calibration,
- just after the maximum calibration temperature
- and when the glass recovers its initial state (72 hours) of maximum temperature



Depression of cero: Abs (max((🔴 - 🟢), (🔵 - 🟢)) = 0.4 ºC

Rectangular distribution

$$u(\delta t_{zero}) = \frac{0.4}{\sqrt{12}} \sim 0.115\ ℃$$

The maximum difference between these three measurements can be considered as the maximum limit for this source of uncertainty.

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Calibration by Comparison. Uncertainty calculation.

The calculation of the calibration uncertainty involves the following steps **in a simplified form**:

1. Express in **mathematical terms** the dependence of the measurand (output quantity: *Y*) on the different input quantities (the different sources of uncertainty: X_i). In the case of a direct comparison of two standards the mathematical model may be very simple: $Y = f(X_i) = X_1 + X_2$.

2. Identify and apply all significant corrections if any.

3. Apply the law of propagation of uncertainties to the mathematical model to calculate the combined standard uncertainty:

Independent input quantities

$$u_c^2(y) = \sum_{i=1}^{N} \left[\frac{\partial f}{\partial x_i}\right]^2 \cdot u^2(x_i)$$

$$u_c^2(y) = \sum_{i=1}^{N} \left[\frac{\partial f}{\partial x_i}\right]^2 \cdot u^2(x_i) + 2 \cdot \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \cdot \frac{\partial f}{\partial x_j} \cdot r(x_i, x_j) \cdot u(x_i) \cdot u(x_j)$$

Correlated input quantities

$Y = X_1 + X_2$

$$u_c^2(y) = u^2(x_1) + u^2(x_2)$$

$$u_c^2(y) = u^2(x_1) + u^2(x_2) + 2r(x_1, x_2)u(x_1)u(x_1)$$

Correlation coeficient

4. Calculate for each input quantity X_i the contribution $u(x_i)$ to the combined standard uncertainty:
   - When a probability distribution can be assumed : $u^2(x_1) = \sigma^2(\overline{x})$ (variance of this distribution) (e.g. calibration uncertainty of the standard thermometers).
   - Of only upper and lower limits (a_+ and a_-) can be estimated, a rectangular probability distribution can be assumed : $u^2(x_1) = \frac{(a_+ - a_-)^2}{12}$ (e.g. manufacturing specifications, hysteresis, thermoelectric homogeneity…)

5. Calculate the expanded uncertainty $U = 2 \times u_c(y)$. If a normal (Gaussian) distribution can be attributed to the measurand a coverage factor $k = 2$ corresponds to a coverage probability of approximately 95 %.

Calibration by Comparison. Uncertainty calculation

For simplicity the uncertainty calibration can be divided in two parts:

- Calculation of the uncertainty of the **reference temperature *T_{ref}***, this is the uncertainty corresponding to the measurement system and will be the same no matter what kind of thermometer is under calibration.
- Calculation of the particular contributions of the **thermometer under calibration** which will depend on the type of sensor.

Calculation of the uncertainty of the reference temperature T_{ref} with one standard

The uncertainty on the determination of the reference temperature comes from the uncertainties of the measurements performed with the standard thermometer and the stability and uniformity of the isothermal enclosure:

$$t_{\mathrm{ref}} = t_{\mathrm{s}} + \delta t_{\mathrm{stab}} + \delta t_{\mathrm{unif}}$$

Using the law of propagation of uncertainties:

$$u^2(t_{\mathrm{ref}}) = u^2(t_{\mathrm{s}}) + u^2(\delta t_{\mathrm{stab}}) + u^2(\delta t_{\mathrm{unif}})$$

Calibration by Comparison. Uncertainty calculation.

Calculation of the uncertainty of the reference temperature *T*$_{ref}$ with two standards

The uncertainty on the determination of the reference temperature comes from the uncertainties of the measurements performed with the standard thermometers and the stability and uniformity of the isothermal enclosure:

$$t_{\mathrm{ref}} = \frac{t_{\mathrm{s1}} + t_{\mathrm{s2}}}{2} + \delta t_{\mathrm{stab}} + \delta t_{\mathrm{unif}}$$

The use of two standard thermometers assures the quality of the calibration. If the two thermometers are similar we can suppose a total correlation between them (correlation coefficient = 1) which simplifies the uncertainty calculation, using the law of propagation of uncertainties:

$$u^2(t_{\mathrm{ref}}) = \left(\frac{1}{2}u(t_{\mathrm{s1}}) + \frac{1}{2}u(t_{\mathrm{s2}})\right)^2 + u^2(\delta t_{\mathrm{stab}}) + u^2(\delta t_{\mathrm{unif}})$$

Assuming similar contributions for each standard thermometer

$$u^2(t_{\mathrm{ref}}) = u^2(t_{\mathrm{s}}) + u^2(\delta t_{\mathrm{stab}}) + u^2(\delta t_{\mathrm{unif}})$$

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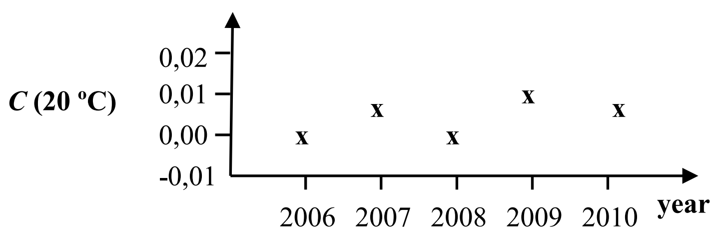
Calibration by Comparison. Uncertainty calculation.

Calculation of the uncertainty of the reference temperature t_{ref}

The uncertainty of the measurements performed by the standards $u(t_s)$ has in turn three main components:

- The **calibration of the standards** $u(t_{s,cal})$, whose contribution can be obtained from the calibration certificate dividing the expanded uncertainty reported by the corresponding coverage factor.
- The **drift** of the standards between calibrations $u(t_{s,drift})$. From the known history of the standards a maximum limit for the drift can be assumed an hence a rectangular probability distribution assigned.



Rectangular distribution

$$u(\delta t_p) = \frac{0.01}{\sqrt{3}} \sim 0.005\,8\ °\mathrm{C}$$

- The **reading of the standards** $u(t_{s,read})$. This uncertainty will depend of the reading system:
  - If the standard thermometers have an indicator , the contribution will come from its resolution to which a rectangular distribution can be assigned.
  - If a resistance bridge is used then the uncertainty will come from the bridge. In the case the contributions are calculated in Ω, the sensitivity coefficient of the thermometer can be used: 0.4 Ω/°C for a pt-100.

Calibration by Comparison. Uncertainty calculation.

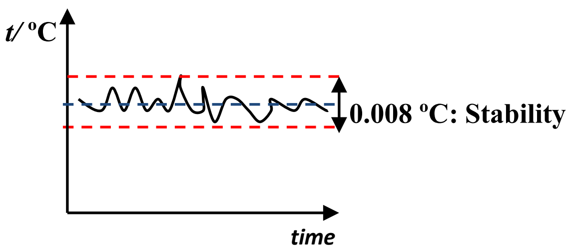
Calculation of the uncertainty of the reference temperature t_{ref}

The contributions due to the **stability and spatial uniformity** of the isothermal enclosure should be estimated previously:

-as the maximum temperature variation of the isothermal enclosure in a determined period of time (stability)

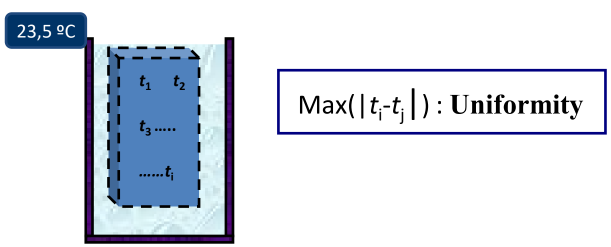
-as the maximum temperature variation of the isothermal enclosure in the useful volume (uniformity).

- in both cases rectangular probability distributions could be assigned.



$$u\left(\delta t_{stability}\right) = \frac{0.008}{\sqrt{12}} \sim 0.002\ 3\ ℃$$

Rectangular distribution



$$u\left(\delta t_{uniformity}\right) = \frac{0.01}{\sqrt{12}} \sim 0.002\ 9\ ℃$$

Rectangular distribution

$$\boxed{u^2(t_{\mathrm{ref}}) = u^2(t_{\mathrm{s,cal}}) + u^2(t_{\mathrm{s,drift}}) + u^2(t_{\mathrm{s,read}}) + u^2(t_{\mathrm{stab}}) + u^2(t_{\mathrm{unif}})}$$

Calibration by Comparison. Uncertainty calculation.

Calculation of the particular contributions of the thermometer under calibration

The thermometer under calibration has two particular contributions:

- The one coming from its **reading** that will depend of the reading system $u(t_{\mathrm{c,read}})$:
- If the thermometer under calibration have an indicator or it is a liquid-in-glass thermometer: resolution + a rectangular distribution;
- If a resistance bridge is used to perform the readings, then the uncertainty will come from the bridge and sensitivity coefficient of instrument needs to be considered:

  Platinum resistance thermometers: 0.4 Ω/°C for a Pt-100.

  Thermistors: the manufacturer specifications should be consulted.

  Thermocouples: depends on the type of thermocouples and the temperature range.

- The contribution which depends on the particular **type of thermometer**, $u(t_{\mathrm{c,part}})$:

Estimated in the additional tests: hysteresis or thermoelectric inhomogeneity or depression of zero.

All of them can be calculated as maximum variation limits and hence rectangular distributions can be assigned in each cases.

In conclusion the combined calibration uncertainty is:

$$\boxed{u^2(t_{\mathrm{c}}) = u^2(t_{\mathrm{s,cal}}) + u^2(t_{\mathrm{s,drift}}) + u^2(t_{\mathrm{s,read}}) + u^2(t_{\mathrm{stab}}) + u^2(t_{\mathrm{unif}}) + u^2(t_{\mathrm{c,read}}) + u^2(t_{\mathrm{c,part}})}$$

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Quantity /x_i	Value/ºC	Type of Distribution	Divisor	Contribution to the combined uncertainty/ ºC $u(x_i)$
Contributions due to the calibration system				
Calibration of the standards (information form the calibration certificate)	*U*certificate/*k*	normal	2	$U/2$
Drift of the standards (information from the standards history)	± drift value	rectangular	$\sqrt{3}$	$\frac{drift\ value}{\sqrt{3}}$
Reading system: combination of the uncertainty calibration, drift, resolution and other characteristics of the reading system	Reading system value	normal	1	*Reading system value*
Stability of the isothermal enclosure (previous studies)	± stability	rectangular	$\sqrt{3}$	$\frac{stability}{\sqrt{3}}$
Spatial uniformity of the isothermal enclosure (previous studies)	± uniformity	rectangular	$\sqrt{3}$	$\frac{uniformity}{\sqrt{3}}$
Particular contributions of the thermometer under calibration				
Resolution/Reading system	resolution	rectangular	$\sqrt{12}$	$\frac{resolution}{\sqrt{12}}$
Characteristics of the sensor (hysteresis or thermoelectric inhomogeneity or depression of zero)	± characteristic value	rectangular	$\sqrt{3}$	$\frac{characteristic\ value}{\sqrt{3}}$
			$u(T)$ =	$\sum_{i=1}^{n} u^2(x_i)$
			$U(T)$ (k=2) =	$2 \cdot u(T)$

Numerical Example:

Calibration of electronic thermometer (resolution 0.1 ºC) with a Pt-100 as sensor (with hysteresis of 0.01 ºC)

Quantity /x_i	Value ºC	Type of Distribution	Divisor	Contribution to the combined uncertainty/ ºC $u(x_i)$
Contributions due to the calibration system				
Calibration of the standards (information form the calibration certificate)	0.020	normal	2	0.010
Drift of the standards (information from the standards history)	0.01	rectangular	√12	0.002 9
Reading system: combination of the uncertainty calibration, drift, resolution and other characteristics of the reading system	0.01	normal	1	0.01
Stability of the isothermal enclosure (previous studies)	0.008	rectangular	√12	0.002 3
Spatial uniformity of the isothermal enclosure (previous studies	0.01	rectangular	√12	0.002 9
Particular contributions of the thermometer under calibration				
Resolution/Reading system	0.1	rectangular	√12	0.02 9
Characteristics of the sensor (hysteresis or thermoelectric inhomogeneity or depression of zero)	0.01	rectangular	√3	0.005 8
			u_c(°C) =	**0.033**
			U(°C) =	**0.066 (k = 2)**

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Thank you
Merci

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