Infrastructure Commission (INFCOM)

Standing Committee on Measurements, Instrumentation and Traceability (SC-MINT)

Expert Team on Quality, Traceability and Calibration (ET-QTC)

Calibration of Temperature Instruments

Part-3: Calibration by Comparison

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Content

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 $\Delta\nu_{Cs}$.

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

-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, the temperature calibrations performed according to ITS-90 are valid and traceable to the SI after the kelvin redefinition

> 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 International Temperature Scale of 1990 (ITS-90).
>
> $$t/°C = T/K - 273.15$$

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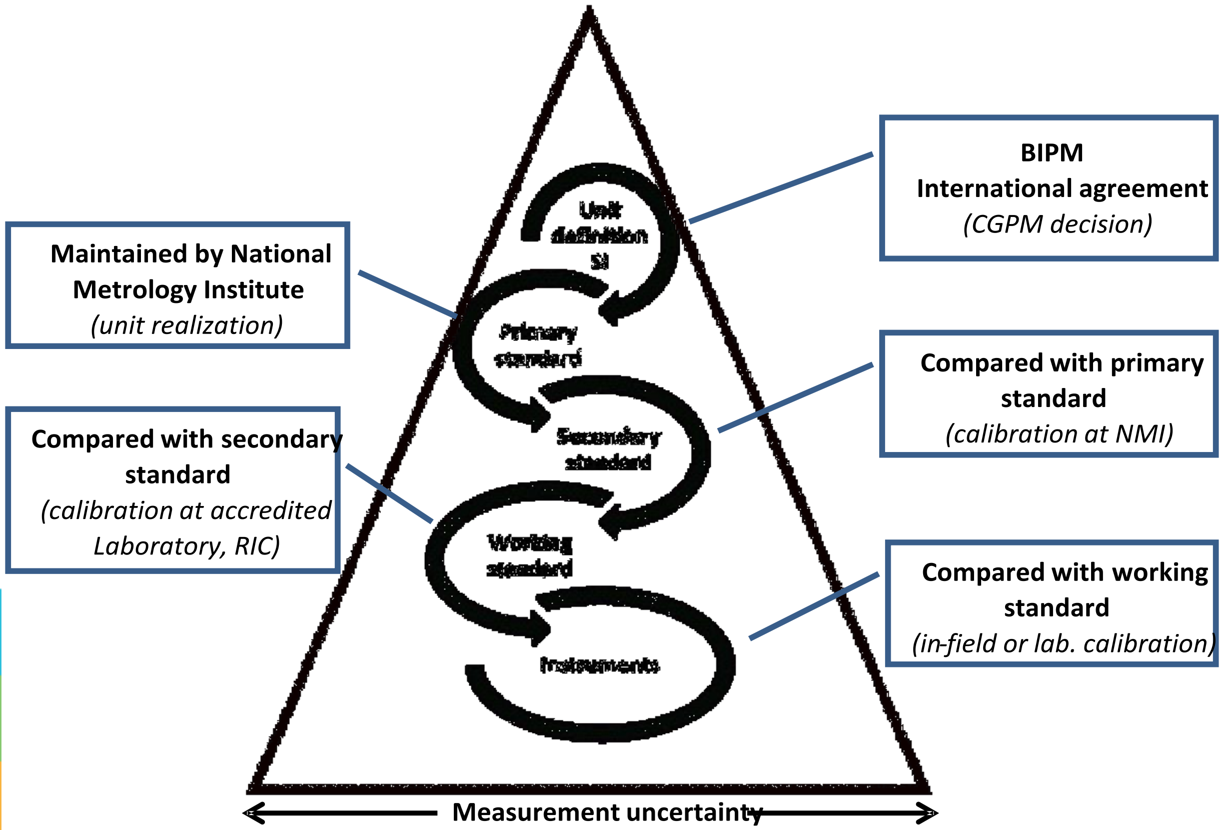
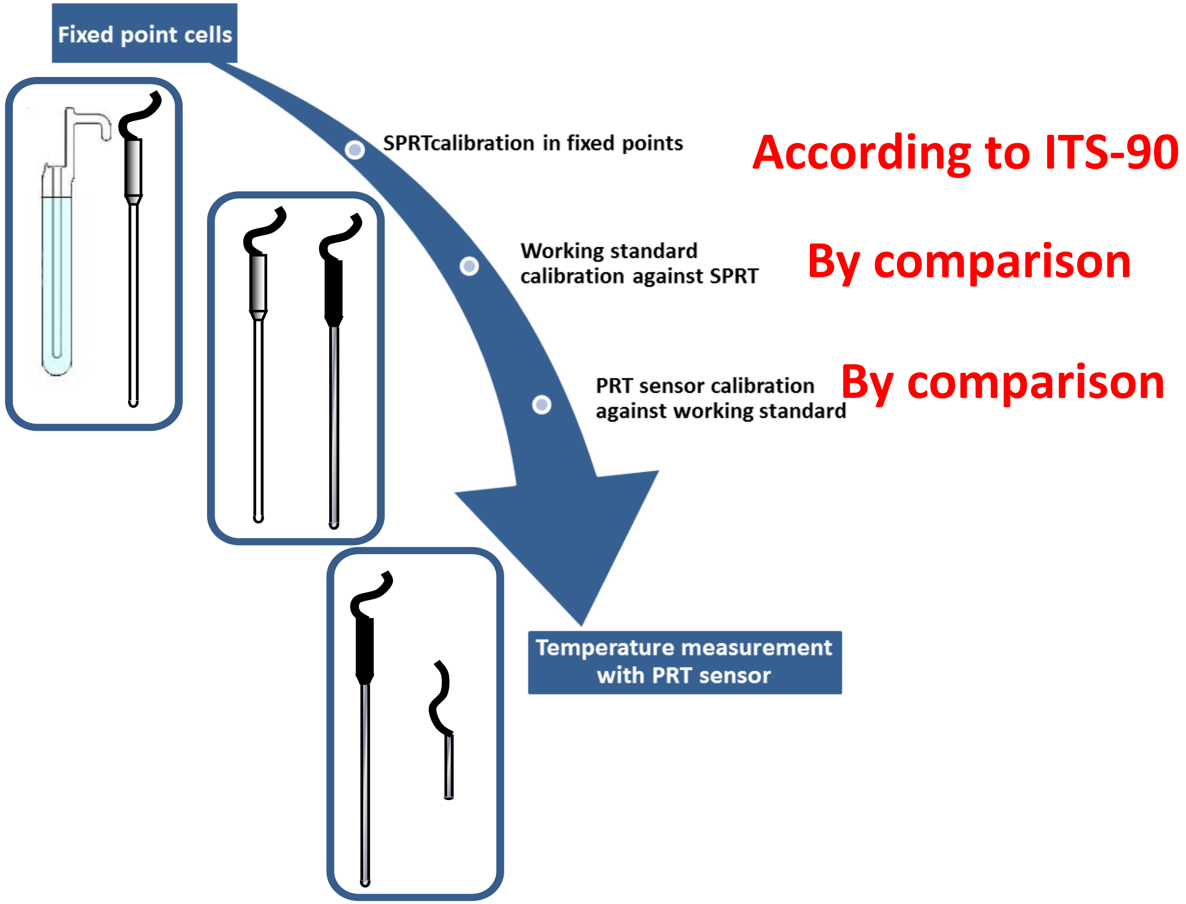
Traceability chain in contact thermometry





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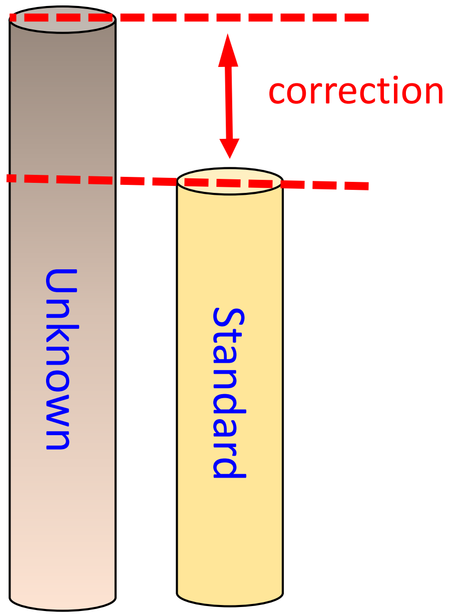
Calibration by Comparison: Definition

-<u>Calibration</u>: 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

-<u>The Calibration by the Comparison Method in contact thermometry</u>: 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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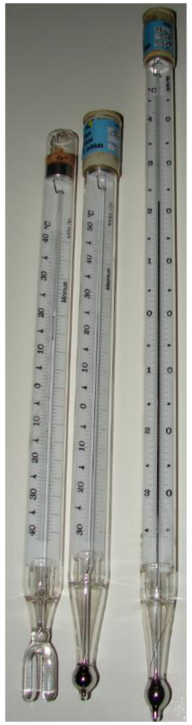
[1] International Vocabulary of Metrology, VIM. www.bipm.org

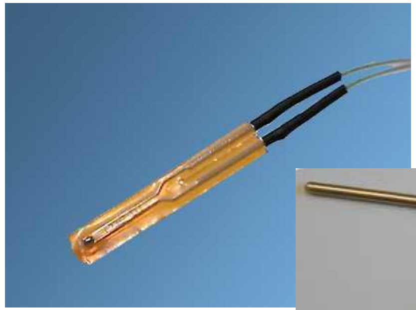
Calibration by Comparison: Types of thermometers

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.

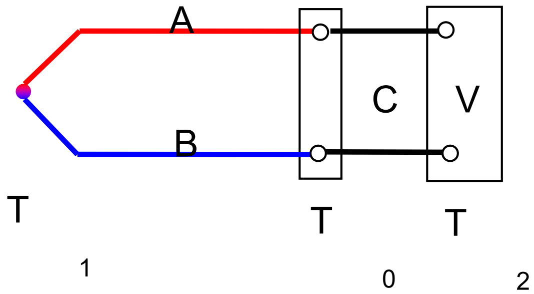


Liquid-in-glass thermometers:
Expansion of a fluid in a capillary stem with temperature

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: Requirements

EQUIPMENT NEEDED:

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

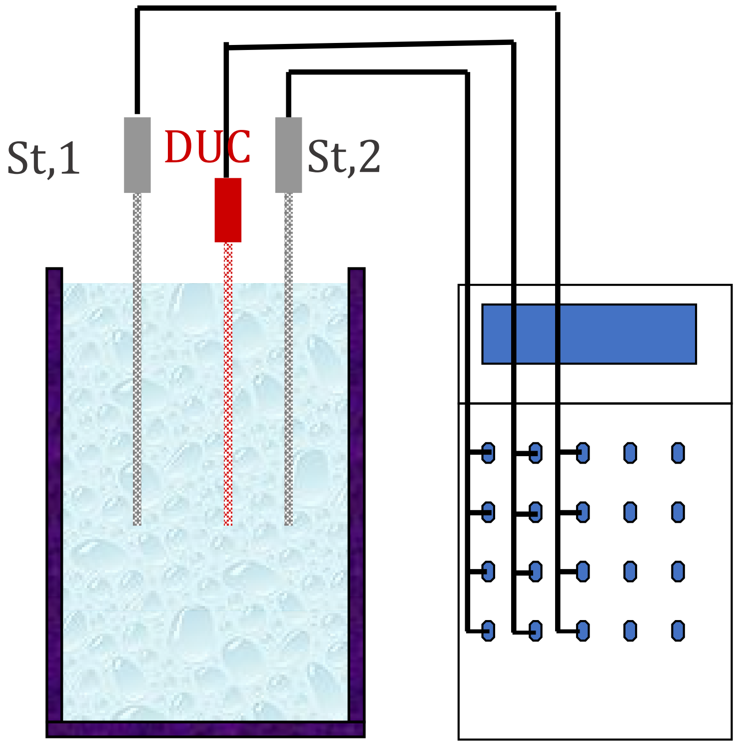
PREVIOUS REQUIREMENTS

- Calibration of the standard thermometer(s) and readout device
- 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.

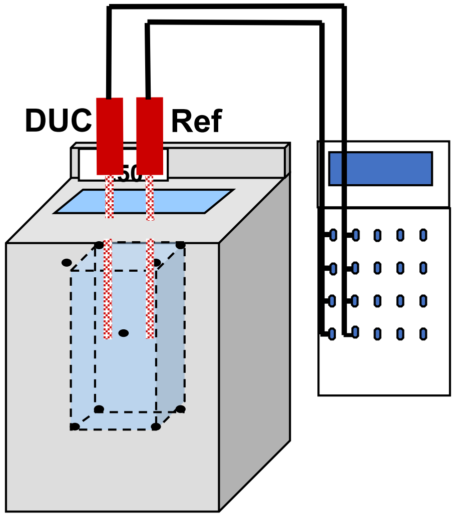
- Determination of the **appropriate immersion depth** of the standard thermometer(s) and the thermometer to be calibrated (DUC, device under calibration), to assure that there are no heat conduction effects.



Calibration by Comparison: One reference thermometer-Data treatment

1) Indications of standard thermometer: I_{St1} I_{DUC}

2) Reading of the thermometers under calibration



3) Using the calibration certificate of the standard: $\boldsymbol{T_{ref}} = f(I_{St1})$

4) The reference temperature of the calibration point is : $\boldsymbol{T_{ref}}$

5) The reading of the thermometer under calibration: $\boldsymbol{I_{DUC}}$

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

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

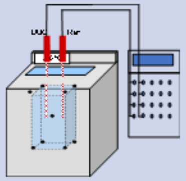
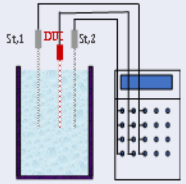
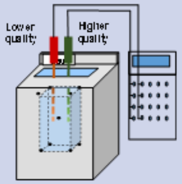
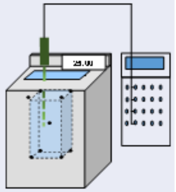
The **uniformity**. <u>This is usually the highest uncertainty source in the calibration of thermometers by comparison (mainly when low calibration uncertainties are required)</u>. Checking it during the calibration process is important.

When low uncertainties are needed, the **standard** is:

Platinum resistance thermometers calibrated in fixed points

Very susceptible to drift → a <u>good control between calibrations</u> of the standard is essential

Control of the appropriate working of **isothermal enclosures** between consecutive characterizations is also needed

Method	Advantages	Disadvantages	Homogeneity: method and value	*T* ref
1 standard 	Lower initial investment	-Requires more time to perform calibrations -High final calibration uncertainty -Impossible to detect problems at early stage -Controls between calibrations are needed for both: the reference thermometer and the isothermal enclosure -Shorter calibration period of the standard and enclosure	By moving the thermometer in the isothermal working volume Homogeneity: $(Is_1max - Is_1min)$	$T_{ref} = f(I_{St1})$
2 standards With the same metrological quality 	-Lowest final calibration uncertainty -Early detection of potential problems: Continuous control of the standards drift, the isothermal enclosure performance and the quality of the liquids in the baths -Additional controls between calibration intervals are not needed -Calibration interval of the reference thermometers and characterization interval of the isothermal enclosure can be extended	-High initial investment -For low uncertainties: The two standards calibrations in in fixed points	By the difference between the readings of the two thermometers Homogeneity: $(I_{s2} - (I_{s1,1} + I_{s1,2})/2)$	$T_{ref} = \dfrac{\dfrac{T_{s1,1} + T_{s1,2}}{2} + T_{s2}}{2}$
2 standards With different metrological quality 	-Low final calibration uncertainty -Early detection of potential problems: Continuous control of the standards drift, the isothermal enclosure performance and the quality of the liquids in the baths -Additional controls between calibration intervals are not needed.	-Initial investment -More often calibrations (of the reference thermometer and isothermal enclosure) than in the case of the two standards of the same metrological quality -For low uncertainties: The standard calibration (with high metrological quality) is in fixed points	By the difference between the readings of the two thermometers. The second thermometer needs a resolution good enough to check the homogeneity Homogeneity: $(I_{s2} - (I_{s1,1} + I_{s1,2})/2)$	$T_{ref} = f(I_{St1})$ Being St1 the thermometer with higher metrological quality
1 standard And Indication of isothermal enclosure as the second standard 	-Limited detection of potential problems in the isothermal enclosure performance	-Calibration of the enclosure indicator is needed -More often standard calibrations than in the case of the two thermometers. -Controls between calibrations are needed for both: the reference thermometer and the isothermal enclosure	By the difference between the thermometer and the bath indicator. The indicator needs a resolution good enough to check the homogeneity Homogeneity: $(I_{indicator} - (I_{s1,1} + I_{s1,2})/2)$	$T_{ref} = f(I_{St1})$ Being St1 the thermometer with higher metrological quality

Calibration by Comparison: Two thermometers-Data treatment

$$I_{St1,1} \rightarrow I_{DUC,1} \rightarrow I_{St2,1} \rightarrow I_{DUC,2} \rightarrow I_{St1,2}$$

Using the calibration certificates of the standards: $\boldsymbol{T_{s1,1}} = f(I_{St1,1})$ $\boldsymbol{T_{s2}} = g(I_{St2,1})$ $\boldsymbol{T_{s1,2}} = f(I_{St1,2})$

The reading of the thermometer under calibration: $\boxed{I_{DUC}(T_{ref}) = \dfrac{I_{DUC,1} + I_{DUC,2}}{2}}$

Reference temperature:

- 2 standards: both of the same metrological quality: $\boldsymbol{T_{ref}} = \dfrac{\frac{T_{s1,1}+T_{s1,2}}{2}+T_{s2}}{2}$
- 2 standards: standard 1 with better metrological quality than standard 2: $\boldsymbol{T_{ref}} = f(I_{St1})$
- 2 standards: Indication of isothermal enclosure as the second standard: $\boldsymbol{T_{ref}} = f(I_{St1})$

Stability check at each calibration point:

$I_{st1,1} - I_{st1,2}$ < stability of isothermal enclosure (previously characterized)

Uniformity check at each calibration point:

$(I_{st2,1} - (I_{st1,1} + I_{st1,2})/2)$ < uniformity of isothermal enclosure (previously characterized)

These checks allow a better assurance of the calibration quality.

Calibration by Comparison: Additional tests

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

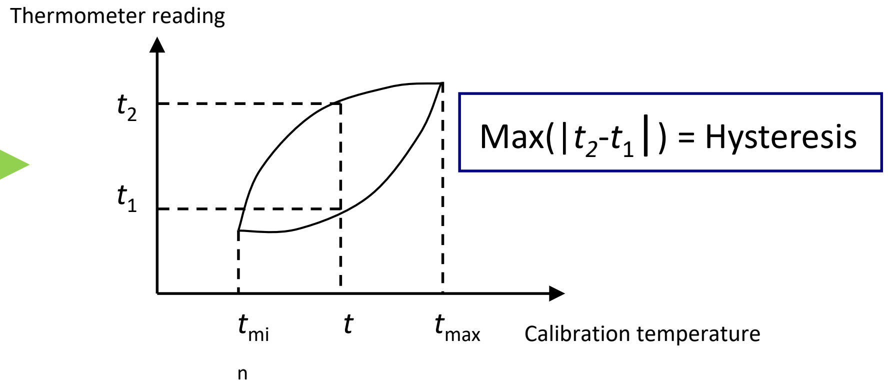
Resistance thermometers → Hysteresis and/or repeatability; Self-heating

Thermocouples → Thermoelectric inhomogeneity

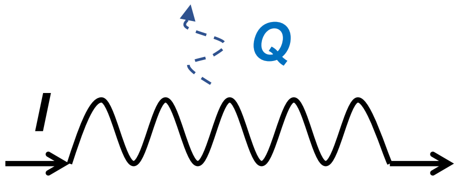
Liquid in glass thermometers → Hysteresis or depression of zero

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



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**.

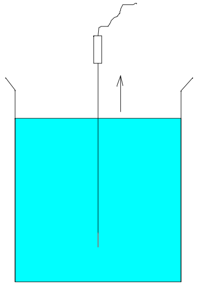
The influence of the self-heating can be evaluated by measuring the variation of thermometer resistance with the measuring current. Commonly, at 1 mA and √2 mA.

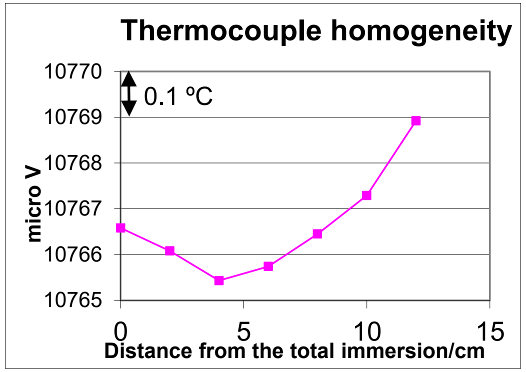
$$(R_{\sqrt{2}\cdot I} - R_I) = Self - heating$$

Calibration by Comparison: Additional tests

Thermoelectric inhomogeneity: Dependency of the thermocouple reading with the temperature gradients. It limits 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).





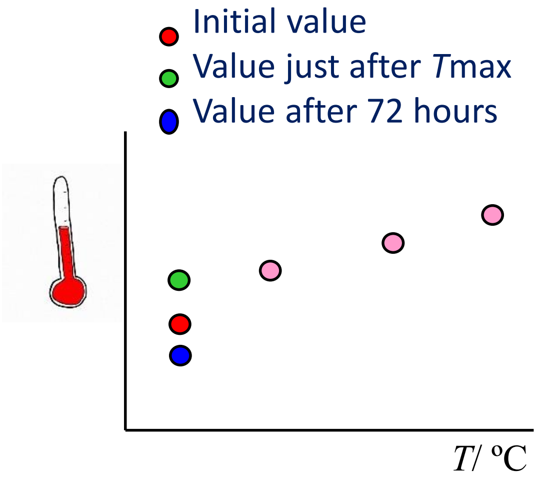
Max(|V_2-V_1|) = inhomogeneity.

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 zero= Abs (max((🔴 -🟢), (🔵- 🟢))



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Thank you.

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