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-1: The International Temperature Scale of 1990 (ITS-90)-Terms, Definitions and Fixed Points

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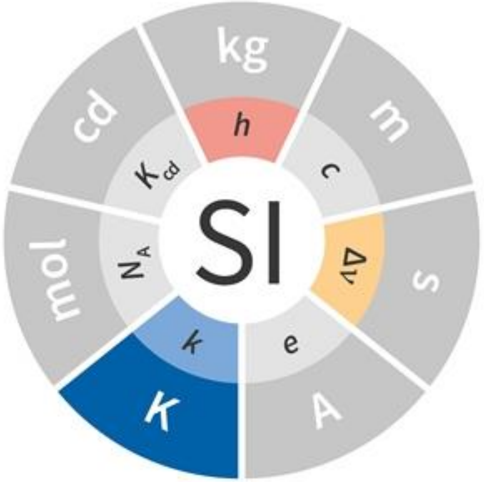
Definitions: Unit of temperature

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.

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).

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

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(1) www.bipm.org

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, measurement technique or temperature range
  - it does not imply any particular method or experiment for its practical realization.

- Direct measurements of thermodynamic temperature require a **primary thermometer** based on a well-understood physical system whose temperature can be derived from measurements of other quantities. Unfortunately, primary thermometry is usually complicated and time consuming, and is therefore rarely used as a practical means of disseminating the kelvin. As a practical alternative, the **International Temperature Scale of 1990 (ITS-90)** provides internationally accepted procedures for both: realizing and disseminating temperature in a straightforward and reproducible manner

- 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 most end users.
  - The temperature calibrations performed according to ITS-90 will be valid and traceable to the SI after the kelvin redefinition.

Definitions: The International Temperature Scale of 1990 (ITS-90)

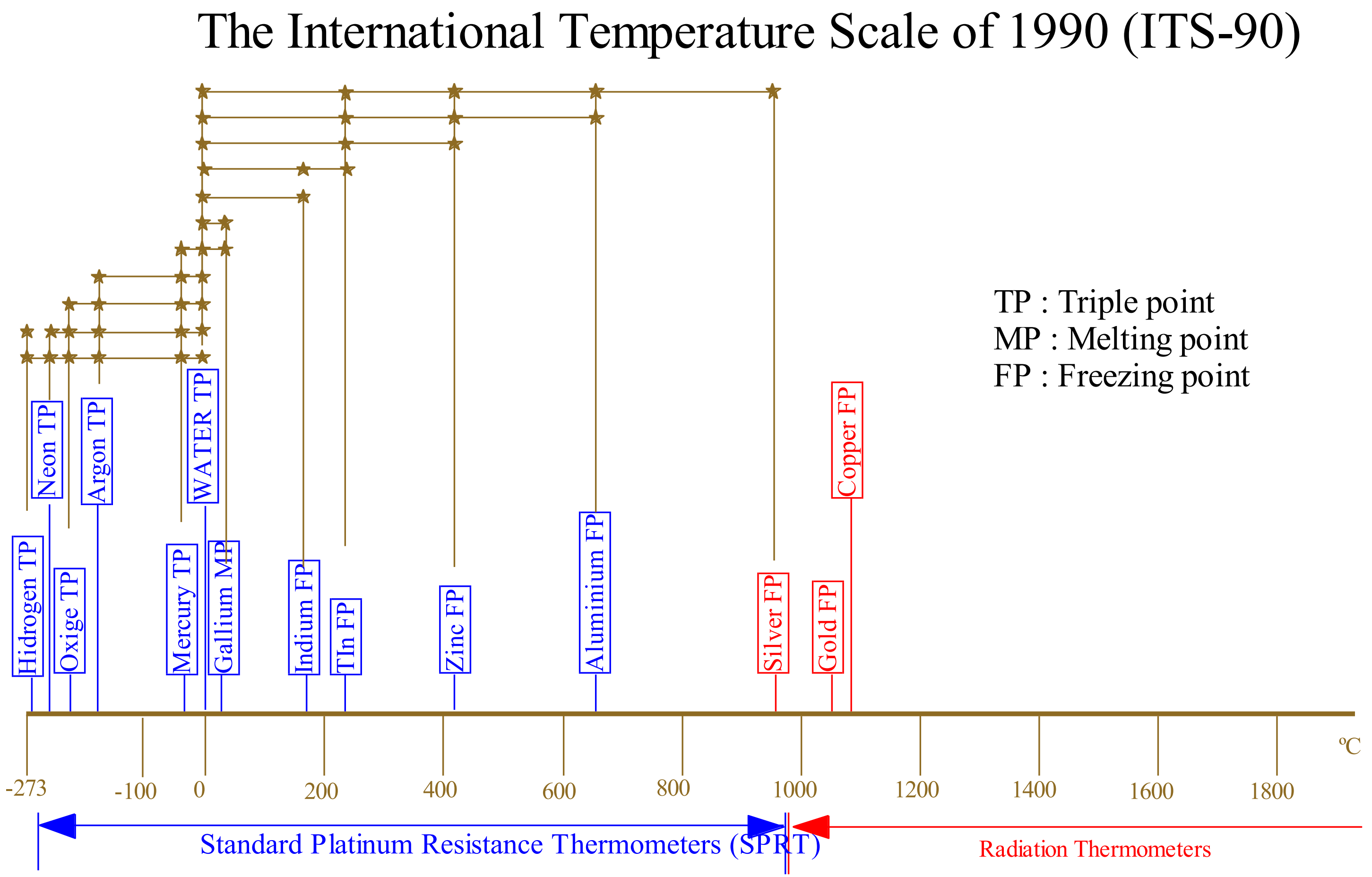
The International Temperature Scale of 1990 (ITS-90) was adopted by the CIPM in 1989.

The ITS-90 extends from 0.65 K up to the highest temperature practicably measurable in terms of the Planck radiation using monochromatic radiation

The ITS-90 comprises ranges and subranges, throughout each of which temperatures T_{90} are defined.

The ITS-90 has three main elements:

- -Defining fixed points
- -Interpolation instruments
- -Interpolation equations



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ITS-90: Defining fixed points

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

V: vapour pressure point

G: gas thermometer point

T: triple point

M: melting point (for a pressure of 101 325 Pa)

F: freezing point (for a pressure of 101 325 Pa)

Temperature		Substance	Estate
T_{90}/K	t_{90}/ºC		
3 a 5	-270,15 a -268,15	He	V
13,803 3	-259,346 7	$e\text{-}H_2$	T
≈17	≈-256,15	$e\text{-}H_2$ (o He)	V (o G)
≈20,3	≈-252,85	$e\text{-}H_2$ (o He)	V (o G)
24,556 1	-248,593 9	Ne	T
54,358 4	-218,791 6	O_2	T
83,805 8	-189,344 2	Ar	T
234,315 6	-38,834 4	Hg	T
273,16	0,01	H_2O	T
302,914 6	29,764 6	Ga	M
429,748 5	156,598 5	In	F
505,078	231,928	Sn	F
692,677	419,527	Zn	F
933,473	660,323	Al	F
1 234,93	961,78	Ag	F
1 337,33	1 064,18	Au	F
1 357,77	1 084,62	Cu	F

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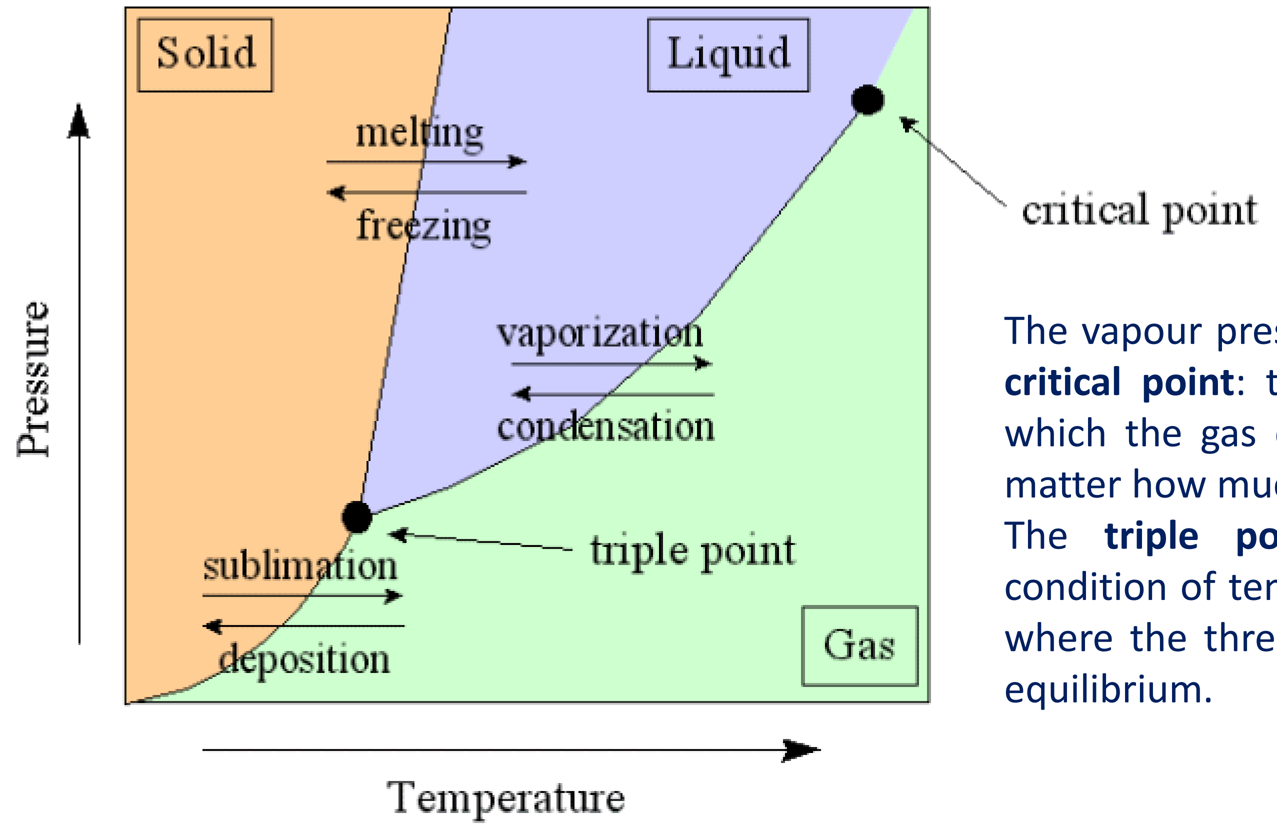
ITS-90: Defining fixed points-Phase diagram of a substance

The curves indicate the conditions of temperature and pressure under which **equilibrium between different phases** of a substance can exist

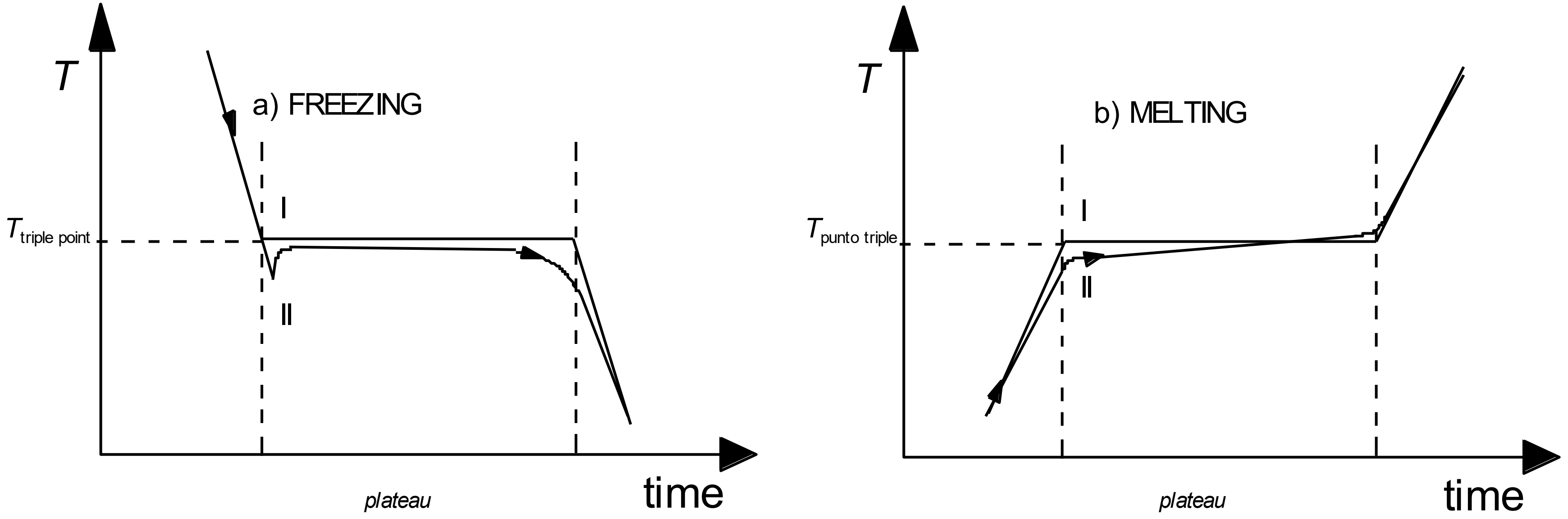


The vapour pressure curve ends at the **critical point**: the temperature above which the gas cannot be liquefied no matter how much pressure is applied.
The **triple point** is the particular condition of temperature and pressure where the three physical states are in equilibrium.

ITS-90: Defining fixed points-Melting and freezing plateaus

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: Defining fixed points-Practical realization of the fixed points

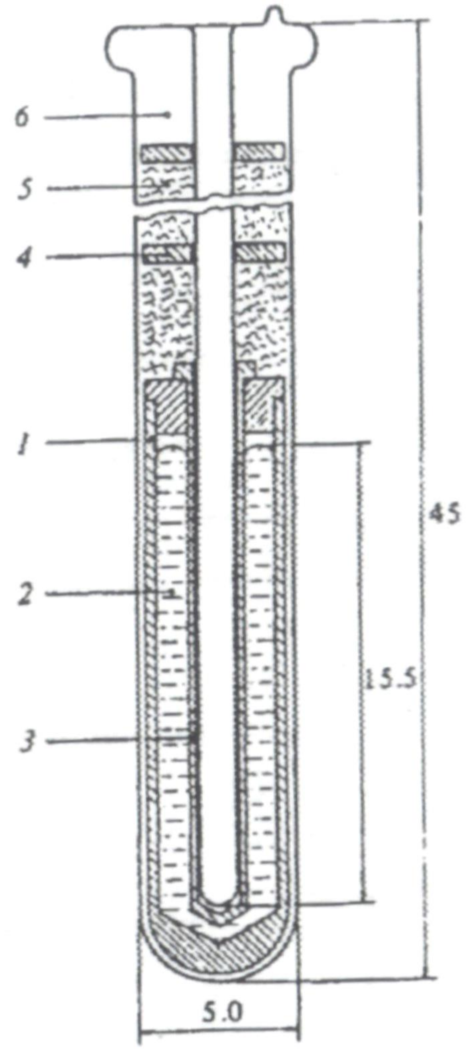
A **fixed point cell** is a practical realization of a fixed point. Essentially it is a cylindrical container or crucible containing a sample of the substance to be frozen or melted and a thermometer well immersed in the sample.

Several factors affect the performance of the fixed point cells:

- **Purity** is the most important source of uncertainty. For instance, to provide reproducibility of 1 mK the purity of the metal fixed points should be 99.9999 % pure.

- They exhibit a temperature dependence on the depth of the cell caused by the **hydrostatic pressure** of the substance and corrections should be applied.

- For melting and freezing points, **pressure** has an influence on the fixed point temperature. Since the fixed point is defined to be at standard atmospheric pressure (101 325 Pa), corrections should be applied if realized at different pressure.



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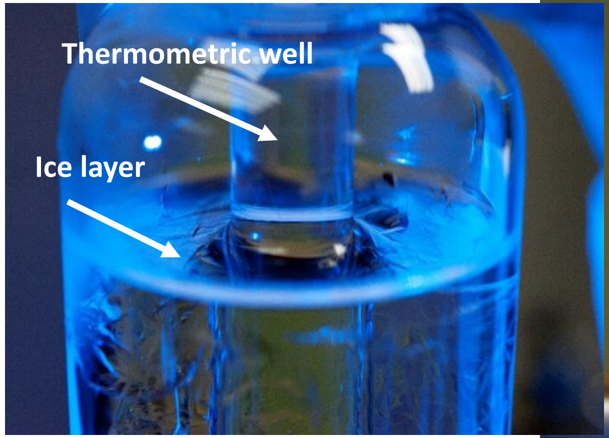
ITS-90: Defining fixed points-The triple point of water

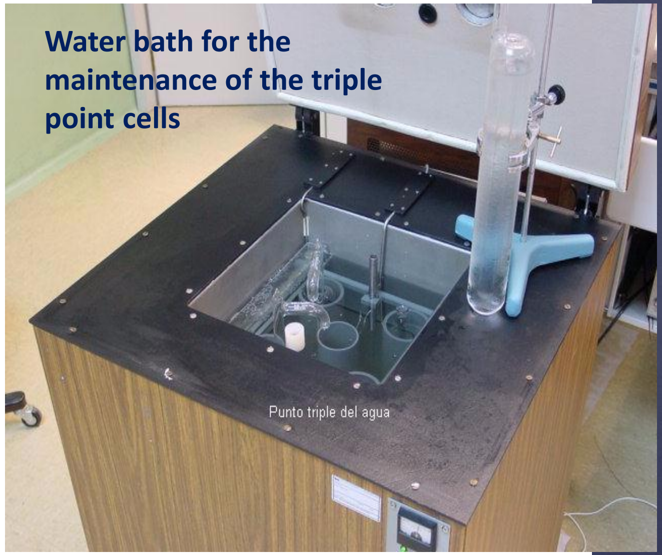
A triple point of water cell contains ice, water and water vapour.

In practice the thermometer needs to be immersed in a place at the triple point temperature. This is achieved with an ice mantle surrounding the thermometer well, with a thin water interface between the ice and the well. This allows the water-ice interface to be in close thermal contact with the thermometer.



To prepare the triple point:

1. The thermometric well is filled with a refrigerant (dry ice, cold nitrogen gas, metal rod cooled in liquid nitrogen…).
2. Once the ice mantle is large enough, the refrigerant is removed and the cell is maintained in an appropriate isothermal enclosure (i.e. water bath).
3. The thin water interface between the ice and the thermometric well by inserting a metal rod at ambient temperature in the thermometric well.



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ITS-90: Defining fixed points-Metal fixed points

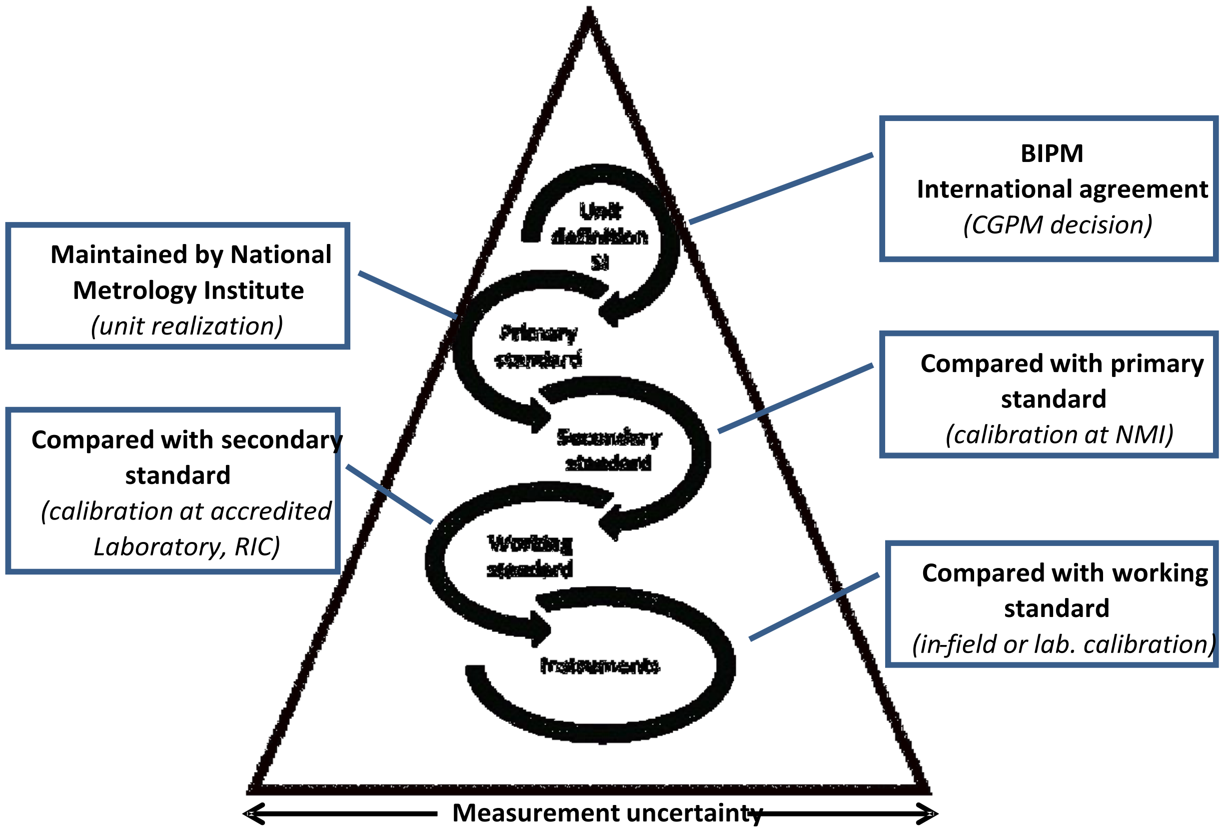
In most cases, the metal sample is contained in a high purity **graphite crucible**, being the thermometric well also made in graphite.

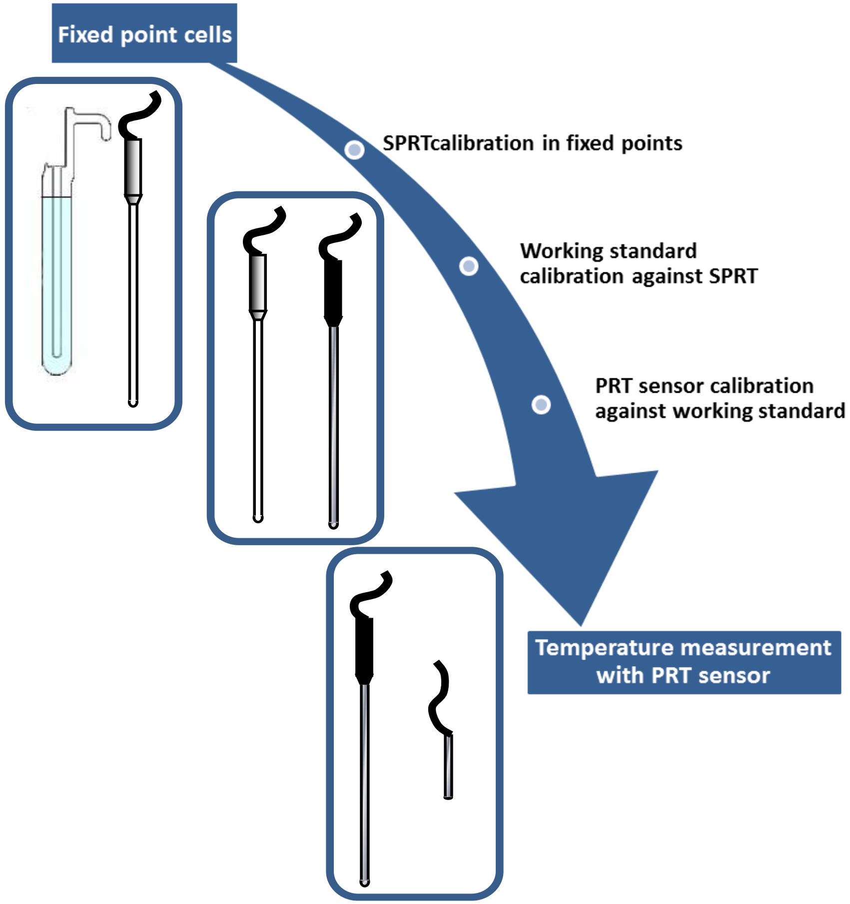
A volume of 100 ml to 250 ml is usually required. **An immersion** of the thermometer of at least 20 cm is needed for optimal realizations.

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.

Traceability chain in contact thermometry





Thank you.

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