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-2: The International Temperature Scale of 1990 (ITS-90)-Interpolation Instruments

Carmen García Izquierdo (CEM)

WORLD METEOROLOGICAL ORGANIZATION

Content

1. Terms and definitions
    1.1. Definitions: Unit of temperature
    1.2. The International Temperature Scale of 1990 (ITS-90)

2. The International Temperature Scale of 1990 (ITS-90):Interpolation instruments
    2.1. Gas thermometers
    2.2. Standard platinum resistance thermometers
    2.3. Radiation thermometers

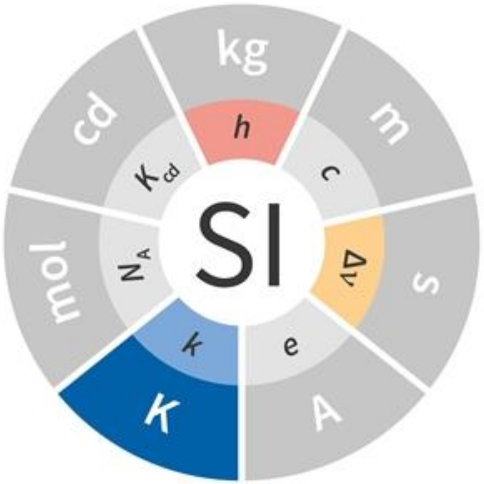
3. Traceability chain in contact thermometry

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).

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

WORLD METEOROLOGICAL ORGANIZATION

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.

WORLD METEOROLOGICAL ORGANIZATION

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

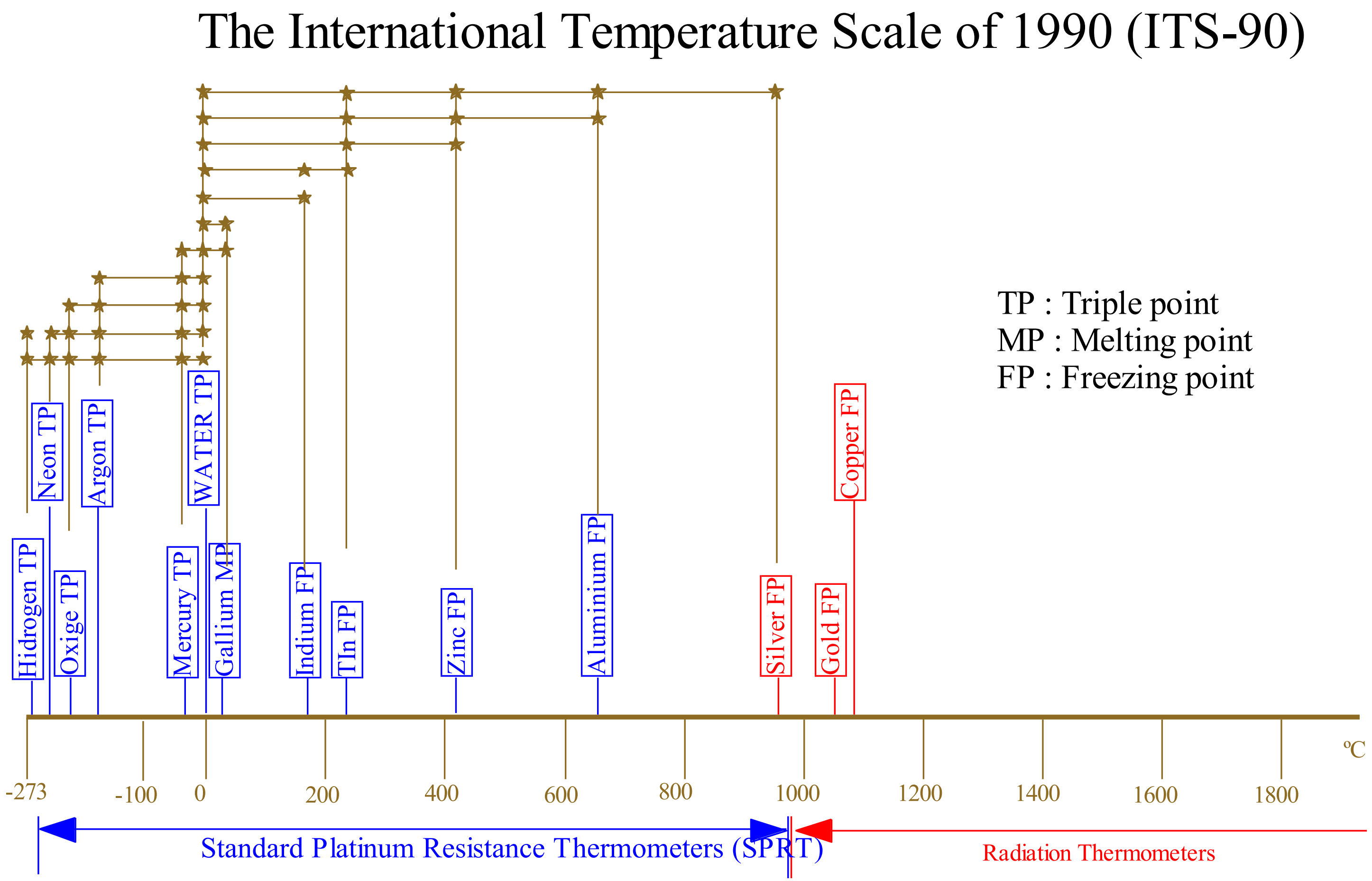
The International Temperature Scale of 1990 (ITS-90) was adopted by the CIPM in 1989.

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



WORLD METEOROLOGICAL ORGANIZATION

ITS-90: Interpolation instruments

The interpolation instruments are highly reproducible thermometers of four different types:

- Helium vapour-pressure thermometers
- Helium or hydrogen gas thermometers
- Standard platinum resistance thermometers
- Radiation thermometers

Gas Thermometers

Between (0.65, 5) K, ITS-90 defines the temperature in terms of the He vapour-pressure thermometer. It is designed to allow two phases of helium (liquid and vapour), to reach the thermal equilibrium in a similar way to the cryogenic triple points. The absolute pressure at the liquid-vapour interface is measured and the temperature calculated.

In the temperature range (3, 24.6) K the ITS-90 interpolation instrument established is the constant-volume gas thermometer (using ^3He or ^4He). It has to be calibrated at three temperatures: the triple points of Ne and equilibrium H_2 and a temperature in the range between 4.2 K and 5 K determined by a vapour-pressure thermometer.

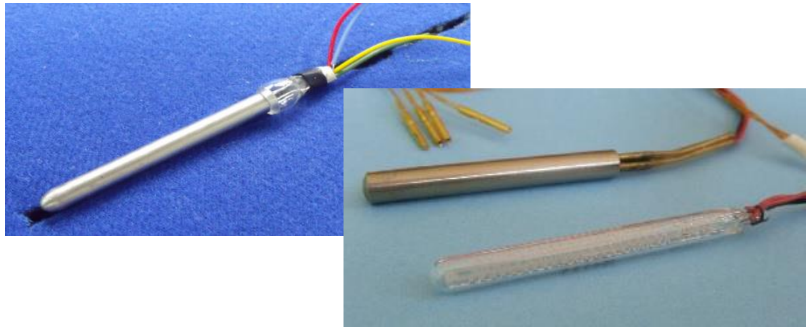
These thermometers are very complicated to operate and they are used only to transfer the scale to other more practical sensors such as capsule type platinum thermometers, rhodium-iron thermometers, etc.

ITS-90: Interpolation instruments

Standard Platinum Resistance Thermometers (SPRT)

Its measurement principle is the change of the electrical resistance in metals with temperature. They can operate from -260 °C to 960 °C with the highest accuracy (better than 1 mK in several ranges) and can even be cycled repeatedly over hundreds of degrees Celsius with optimal repeatability and reproducibility. There are three different types of SPRTs designed to cover different temperature ranges:

- **Capsule SPRTs**: from 13.8 K to 157 °C. They have small dimensions (around 50 mm long and 5 mm diameter) with 25.5 Ω resistance at the triple point of water. Usually filled with He to improve the thermal contact and the response time.



- **Long-stem SPRTs**: from 84 K to 660 °C. Their dimensions are around 450 mm long and 8 mm diameter. Encapsulated in glass or quartz tubes and with 25.5 Ω resistance at the triple point of water. Usually filled with an inert gas plus a certain amount of O_2 to control the oxidation state of Pt.

- **High-temperature SPRTs**: from 0.01 °C to 962 °C. They are long-stem SPRTs constructed (using quartz sheaths) to be exposed at higher temperatures. The nominal resistance at the triple point of water is 0.25 Ω to reduce the influence of insulation leakage effects.

ITS-90: Interpolation instruments

Standard Platinum Resistance Thermometers (SPRT)

The quantity of interest for SPRTs is not the absolute resistance value of the thermometer $R(T_{90})$, but the resistance ratio with respect the resistance at the triple point of water:

$$W(T_{90}) = \frac{R(T_{90})}{R(273{,}16\ K)}$$

The main reason for that is to eliminate the uncertainties associated with the measurement of the absolute resistance.

The ITS-90 requires that the SPRTs as interpolation instruments need to fulfill (only possible with Pt wire pure enough):

- $W(29.7646\ ^\circ\mathrm{C}) \geq 1.118\ 07$
- $W(-38.8344\ ^\circ\mathrm{C}) \leq 0.844\ 235$
- $W(961.78\ ^\circ\mathrm{C}) \geq 4.2844$

The ITS-90 defines reference functions to relate the change of the resistance ratio (W) with the temperature and simple interpolation equations for the calibration of a particular SPRT.

ITS-90: Interpolation instruments

Standard Platinum Resistance Thermometers (SPRT): Interpolation equations

The **reference functions** are:

$$T_{90} < 0 \quad \ln[W_r(T_{90})] = A_0 + \sum_{i=1}^{12} A_i \cdot \left[\frac{\ln\left(T_{90}/273{,}16\ \mathrm{K}\right) + 1{,}5}{1{,}5} \right]^i$$

$$T_{90} > 0 \quad W_r(T_{90}) = C_0 + \sum_{i=1}^{9} C_i \left[\frac{T_{90}/\mathrm{K} - 754{,}15}{481} \right]^i$$

The calibration equations for individual thermometers are written as interpolations of the form:

$$W_\mathrm{r}(T_{90}) = W(T_{90}) - \Delta W(T_{90})$$

$\Delta W(T_{90})$ are the so-called **deviation functions**:

The ITS-90 defines 11 different subranges with 11 different deviation functions.

The coefficients of the deviation functions are calculated by calibrating the SPRT in the fixed points corresponding to the desired calibration range.

For instance, if the user requires to measure temperature around 20 °C, the related ITS-90 temperature subrange would be from the triple point of water (0.01 °C) to the Ga melting point (29.7646 °C) which requires just two fixed points: water and Ga.

ITS-90: Interpolation instruments

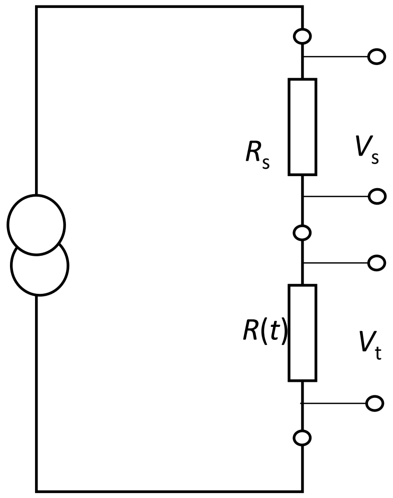
Standard Platinum Resistance Thermometers (SPRT): Measurement instruments.

To achieve accurate measurements of temperature by using SPRTs, automatic resistance bridges are required.

There are two basic methods to measure resistance:

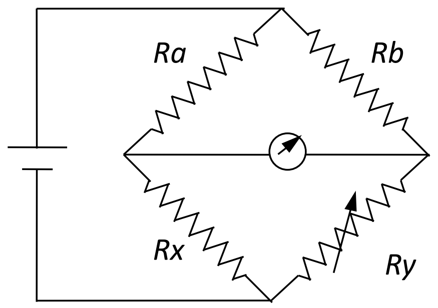
- **Potentiometric methods**: a current is passed through both the standard resistor (R_s) and the thermometer ($R(t)$). As the current is the same, the measured voltages are in the ratio of the resistances. This technique is used in almost all digital multimeters.

Potentiometric method



$$R(t) = \frac{V_s}{V_t} R_s$$

Wheatstone Resistance Bridge



$$\frac{R_x}{R_y} = \frac{R_a}{R_b}$$

- **Bridge methods**: based on the Wheatstone bridge, a null detector compares the output voltage from two voltage dividers, one of them including the resistance thermometers.

WORLD METEOROLOGICAL ORGANIZATION

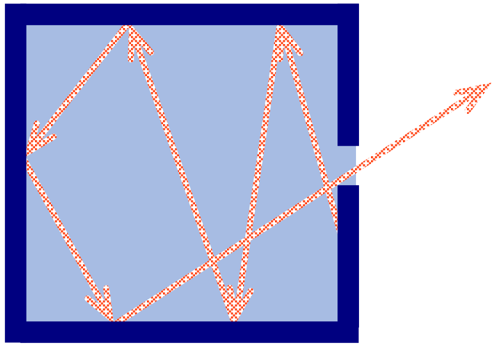
ITS-90: Interpolation instruments (T > 961.78 ºC).

Radiation thermometers

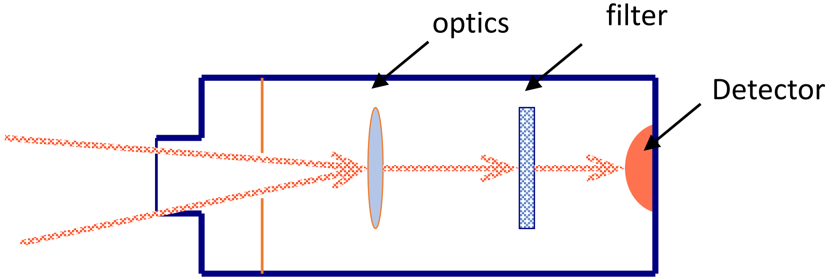
Above the freezing point of silver, the ITS-90 uses the Plank blackbody radiation law to define the temperature in terms of the **spectral radiance** at the temperature T_{90}:

$$\frac{L_\lambda(T_{90})}{L_\lambda(T_{90}(x))} = \frac{e^{c_2/\lambda \cdot T_{90}(x)} - 1}{e^{c_2/\lambda \cdot T_{90}} - 1}$$

Where T_{90} (x) is either the fixed point temperature of Ag, Au or Cu, L_λ is the spectral radiance at the λ wavelength in vacuum and c_2 = 0.014 388 m K is the second Plank constant.



Blackbody



Radiation Thermometer

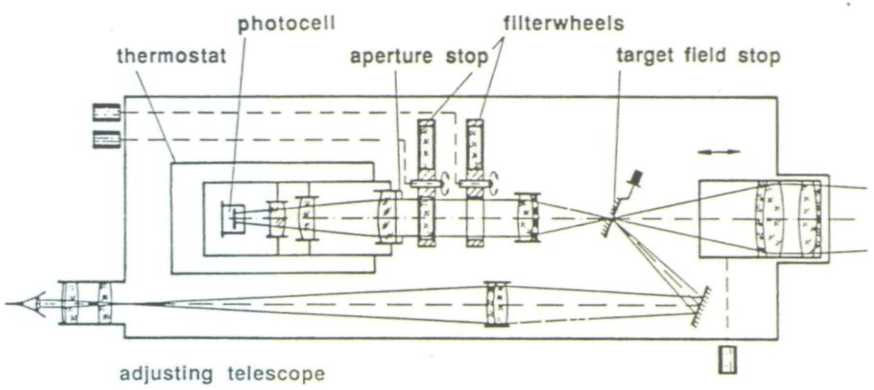
WORLD METEOROLOGICAL ORGANIZATION

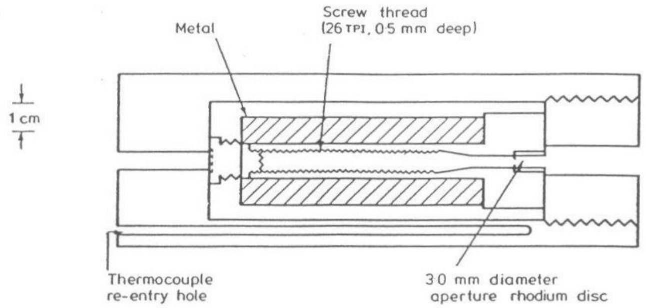
ITS-90: Interpolation instruments (T > 961.78 ºC).

Radiation thermometers: Requirements

- The radiation thermometer used as an ITS-90 interpolation instrument should be **monochromatic** and **linear.**

- The radiation source should be a **blackbody** (emissivity close to 1). In practice it is a furnace with a Ag, Au or Cu fixed-point cell. The fixed-point cells for radiation thermometry are similar to those for SPRTs but smaller. The crucible are mounted horizontally in the furnace and the graphite well is made into a blackbody cavity with aperture from 2 mm to 6 mm.



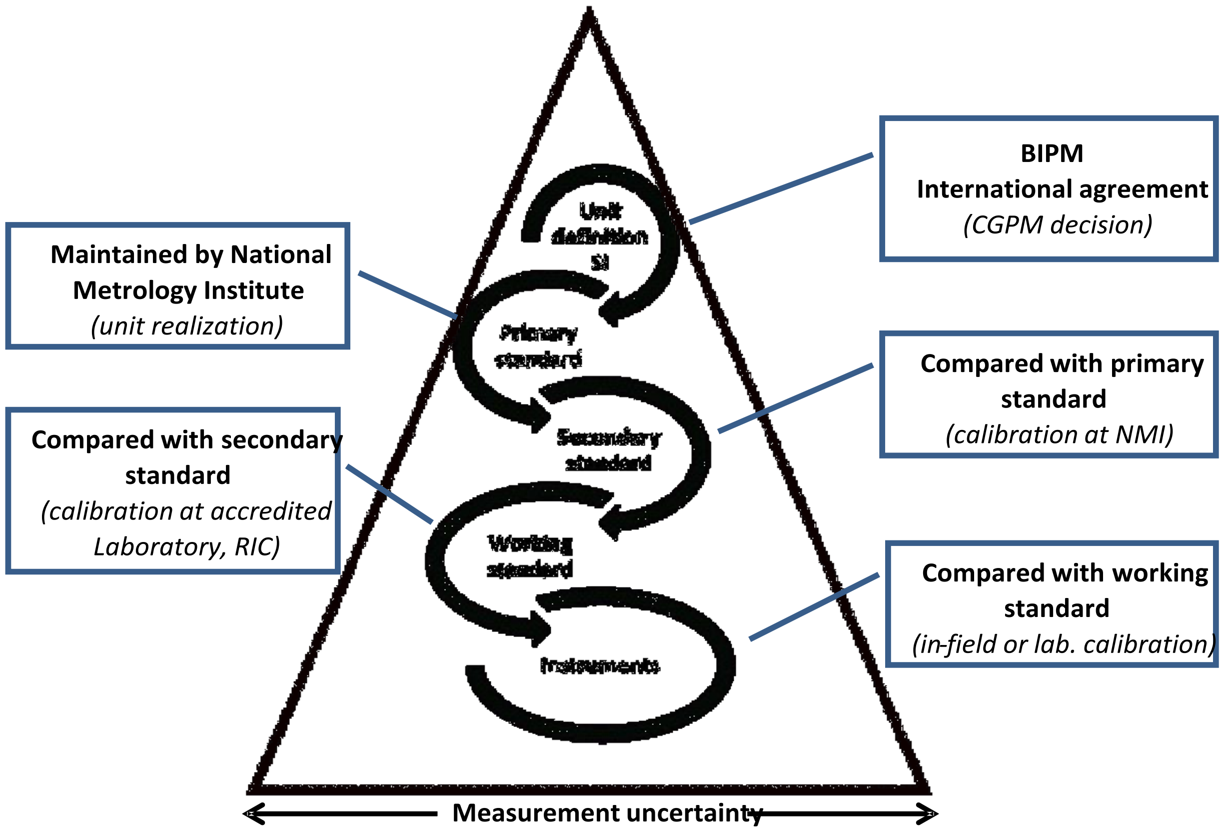


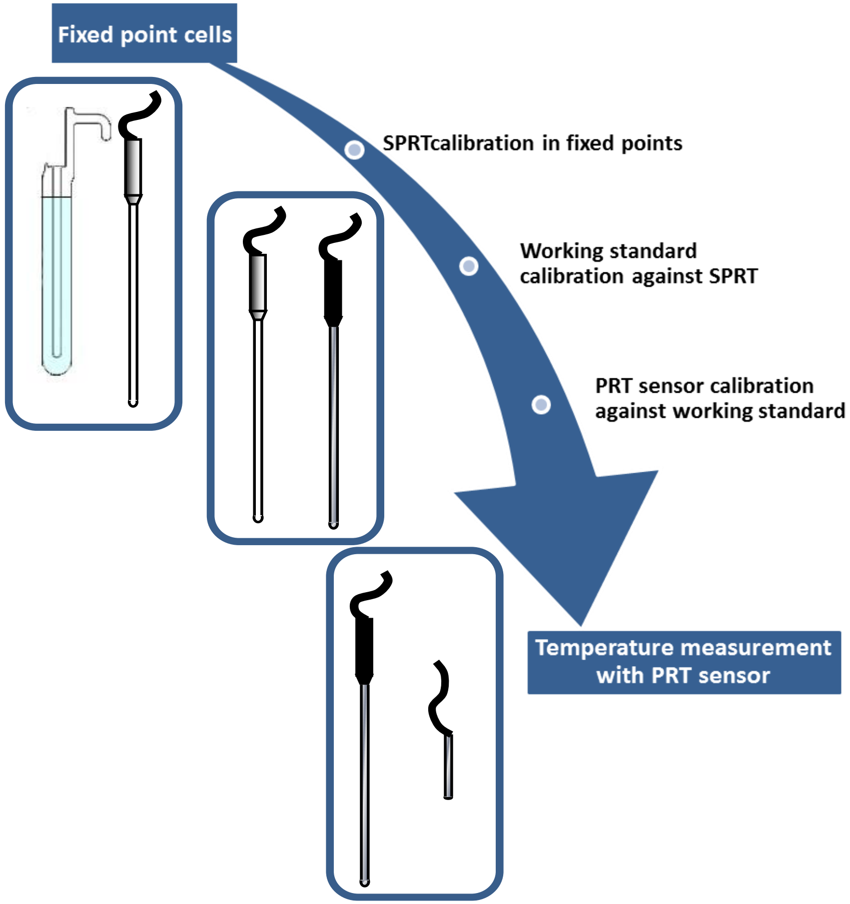
- The three fixed points (Ag, Au and Cu) are equivalent.

- The accuracy of radiation thermometers is around 0.1 K at the Ag point. At higher temperatures the uncertainty increases with T^2.

WORLD METEOROLOGICAL ORGANIZATION

Traceability chain in contact thermometry





WORLD METEOROLOGICAL ORGANIZATION

Thank you.

WORLD
METEOROLOGICAL
ORGANIZATION

wmo.int