Lesson 12

Thermomechanical Measurements for Energy Systems (MENR)

Measurements for Mechanical Systems and Production (MMER)

A.Y. 2015-16

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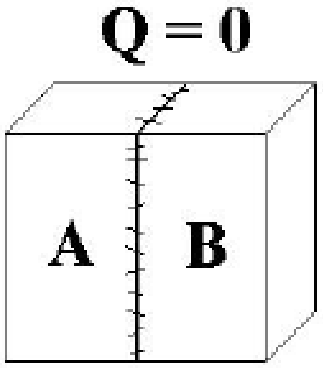
The measurement of the TEMPERATURE

If a certain amount of ***heat Q*** is supplied or subtracted from a body, this will change its ***temperature T***.
The heat Q (which is a form of energy and is measured in *Joule*) alters the molecular activity of the bodies, causing variation of the temperature T. Therefore, it follows immediately that the temperature is a quantity that provides a status information about the "energy state" of the body.

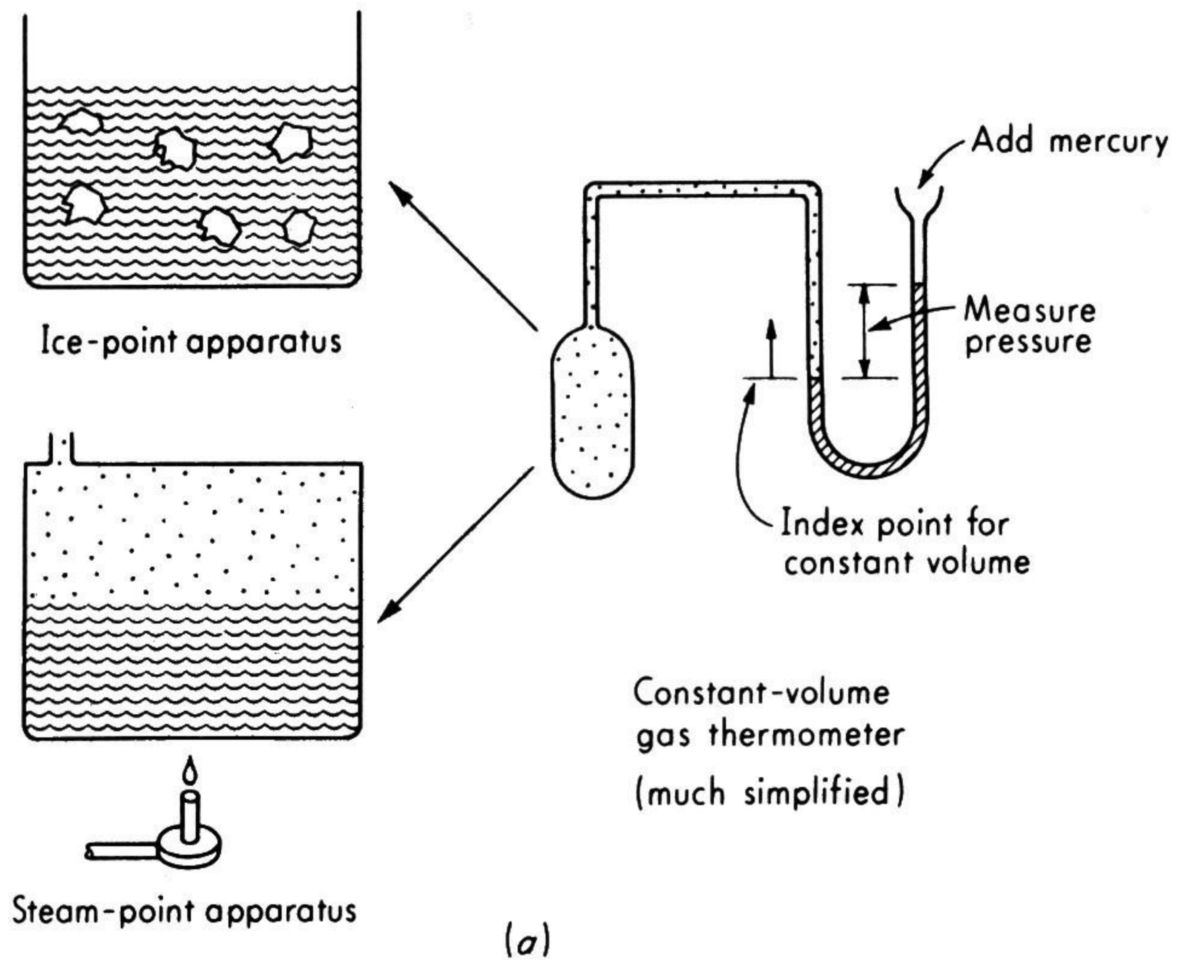


We can refer to the ***zero law of thermodynamics***: if there is *thermal equilibrium*, or there is *no heat Q exchange* between two bodies A and B placed in contact, the *bodies A and B are at the same temperature* !
This property is transitive: if there is a *thermal equilibrium between the bodies A and B* and *between the bodies B and C*, there is also *thermal equilibrium between the bodies A and C,* although not in contact …

However, the "operative methods" for the ***measurement of temperature*** are realized by means of the properties of bodies and materials and their change with temperature …

- the variations of physical dimensions → the volume ΔV or the length Δl, according to the form of the body;
- the variations of electrical properties → the resistance ΔR;
- the variations of physical state → from solid to liquid, to vapor or vice versa, very useful to define the reference temperatures T (see below).

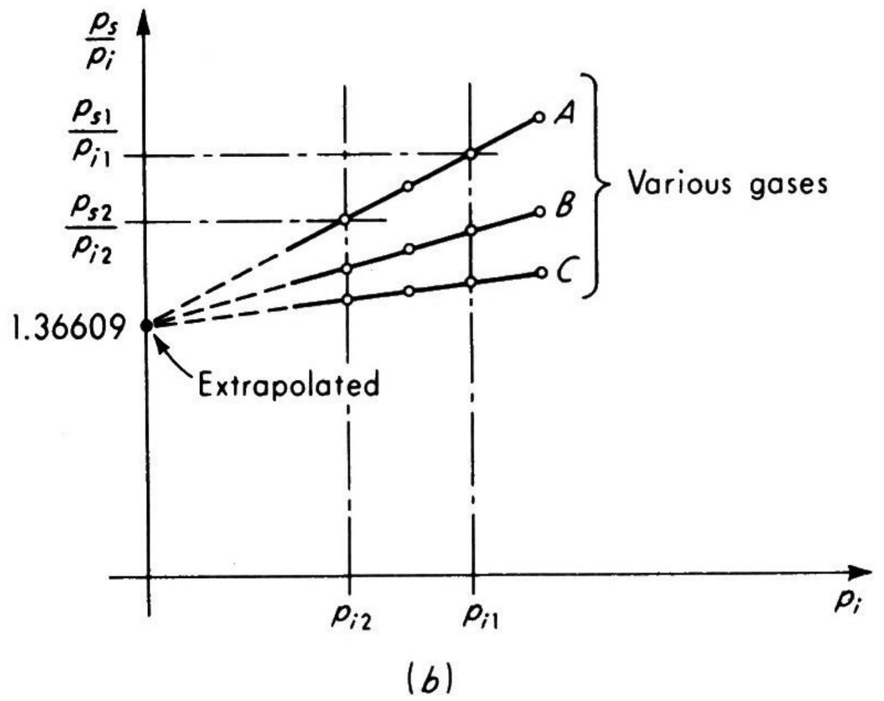
The gas thermometer experience:



applies the Boyle's law: $pV = nRT$

$\frac{p_1}{p_2} = \frac{T_1}{T_2}$ … at V = cost …

$\frac{p_s}{p_i} = \frac{T_s}{T_i}$ = 1,36609 …



Gas-thermometer temperature scale.

because <u>we wont</u> $T_s = T_i + 100$ we write $\frac{T_i+100}{T_i}$ = *1,36609 …*

so we get *0,36609·T_i = 100* and $\boldsymbol{T_i = 273{,}16}$ [K]

The official temperature scale (IS) is the *thermodynamic scale* where the *temperature unit* is the **_kelvin K_** but, it is also **_1 K = 1 °C_**

For *calibrating* all industrial thermometers, six *fixed temperature points* are recommended, defined as the *equilibrium temperatures between 2 phases* between: solid/liquid/vapor at the standard pressure of 1 atmosphere (101325 Pa).

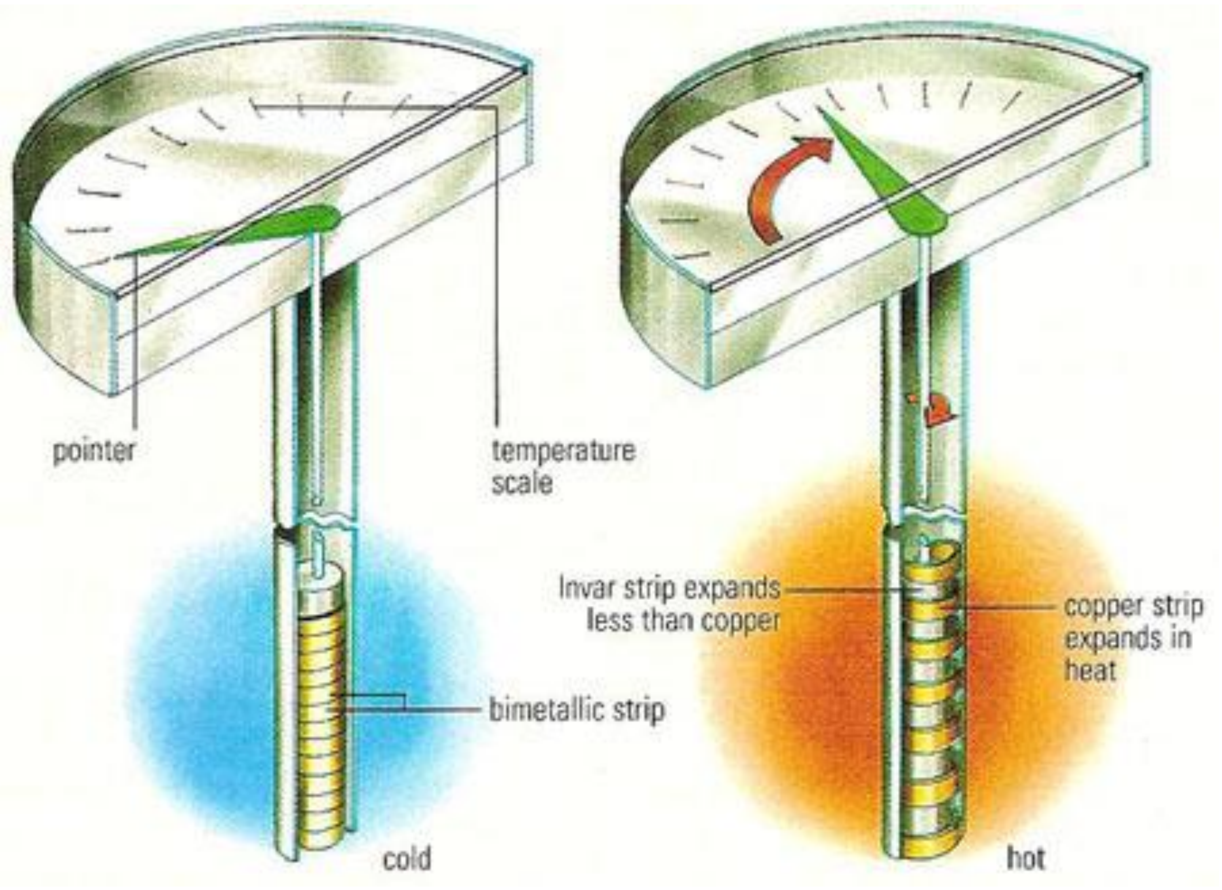
1. Oxygen point (-182.96°C): equilibrium T between O(L) and O(V)
2. Water triple point (+0.01°C): equilibrium T between H_2O(S) , H_2O(L) , H_2O(V)
3. Water vapor point (+100°C): equilibrium T between H_2O(L) e H_2O(V)
4. Zync point (+419.58°): equilibrium T between Zn(S) e Zn(L)
5. Silver point (+961.93°C): equilibrium T between Ag(S) e Ag(L)
6. Gold point (+1064.43°C): equilibrium T between Au(S) e Au(L)

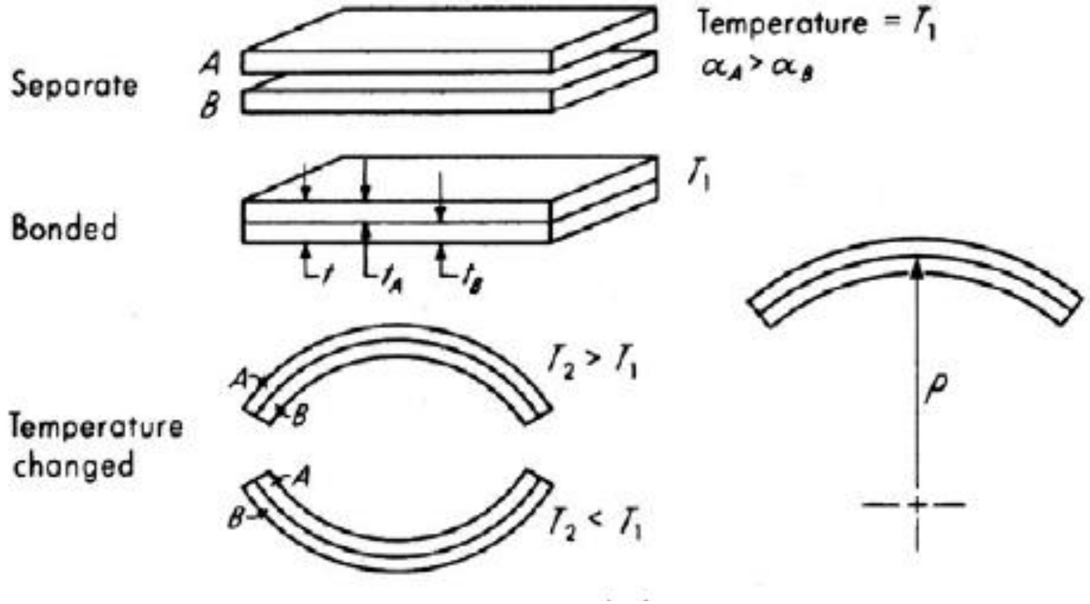
ITS-90 Fixed-Point Cells

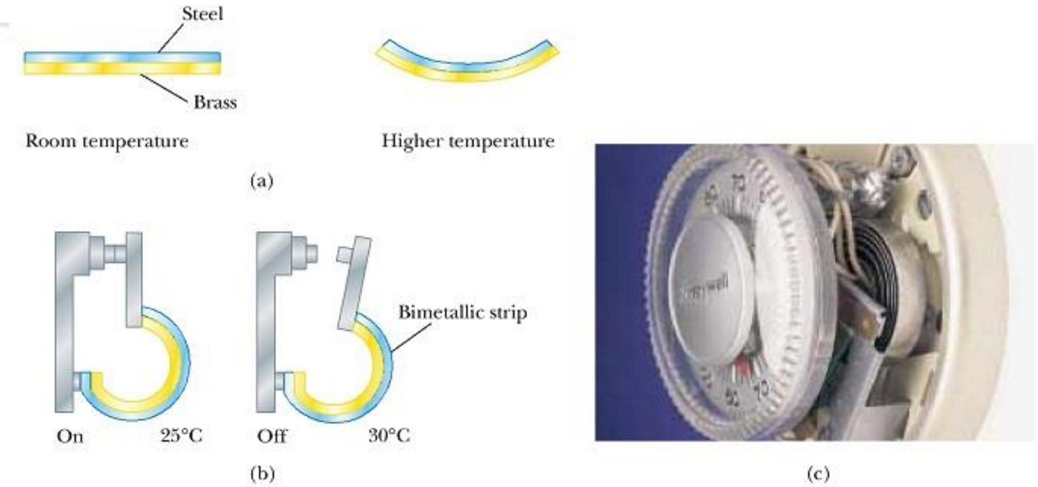
The **International Temperature Scale of 1990** (***ITS-90***) is the "de facto" standard used in the industrialized world by international convention

Bimetallic Thermometers :

Mostly used as ***automatic thermal switches*** for safety temperature monitoring !

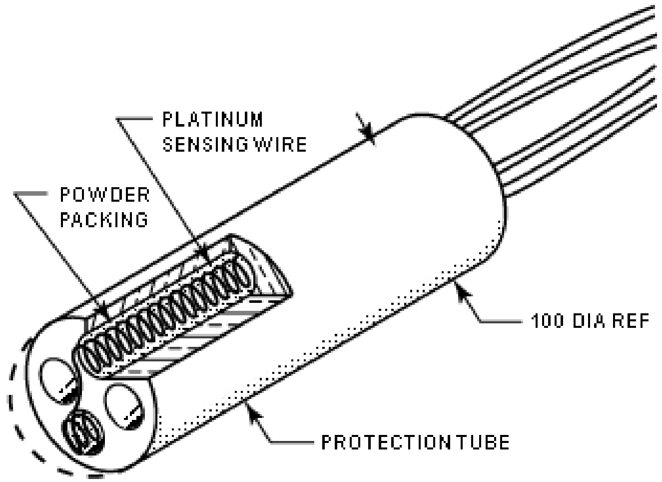






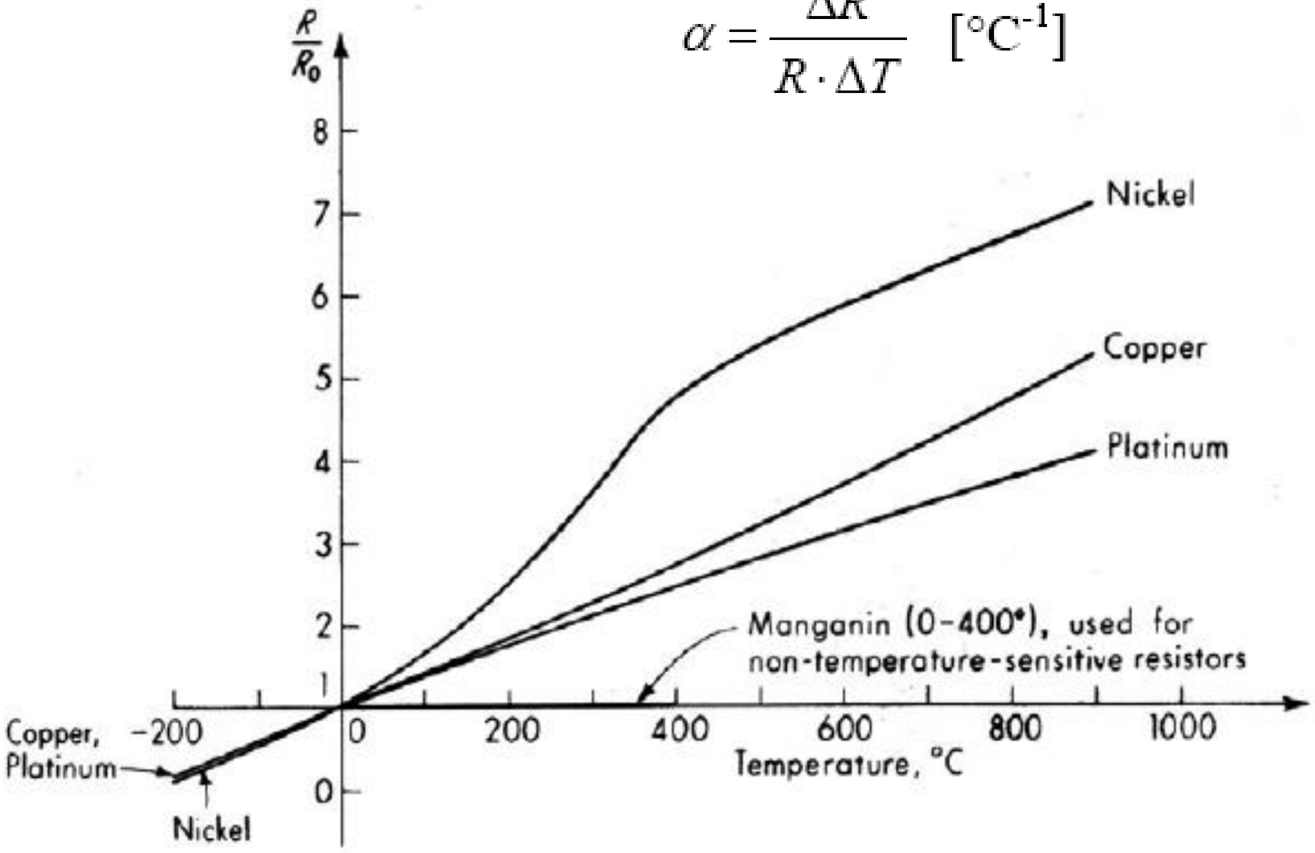
Electric industrial Thermometers :

Resistance temperature Detectors (RTD): Pt100



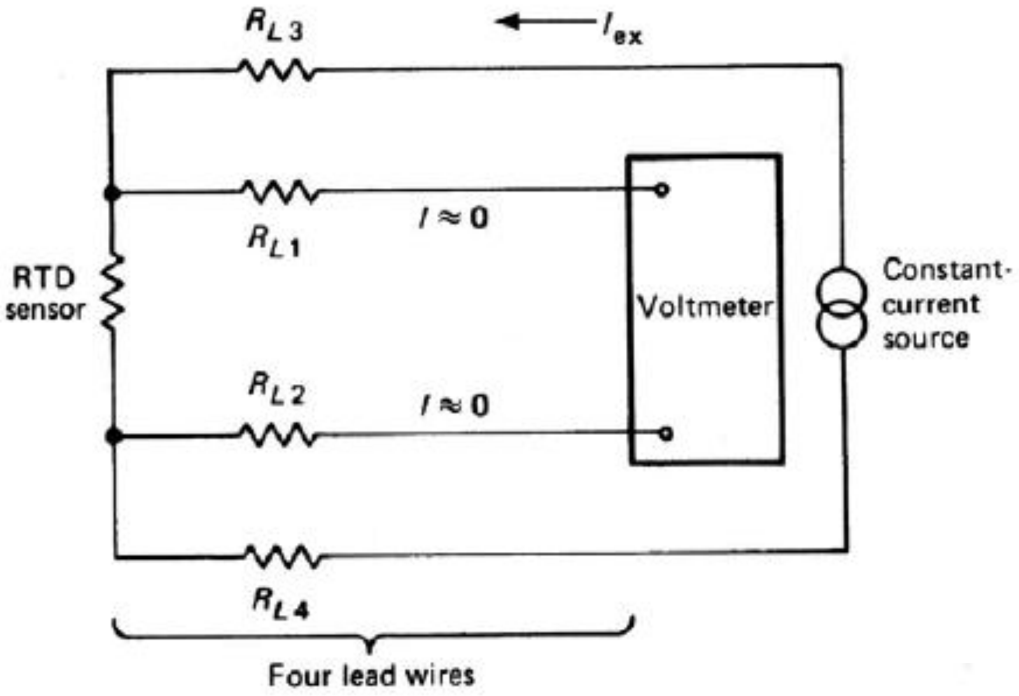
$$R_T = R_0\left(1+\alpha\Delta T\right)$$

$$\alpha = \frac{\Delta R}{R\cdot\Delta T} \quad [°C^{-1}]$$



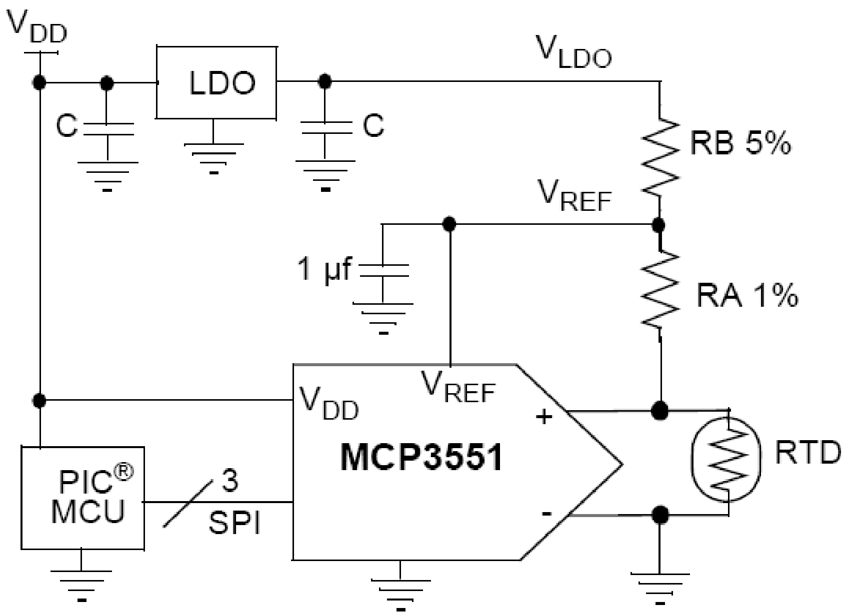
Resistance/temperature curves.

Signal conditioning and correct circuit connections for RTD :

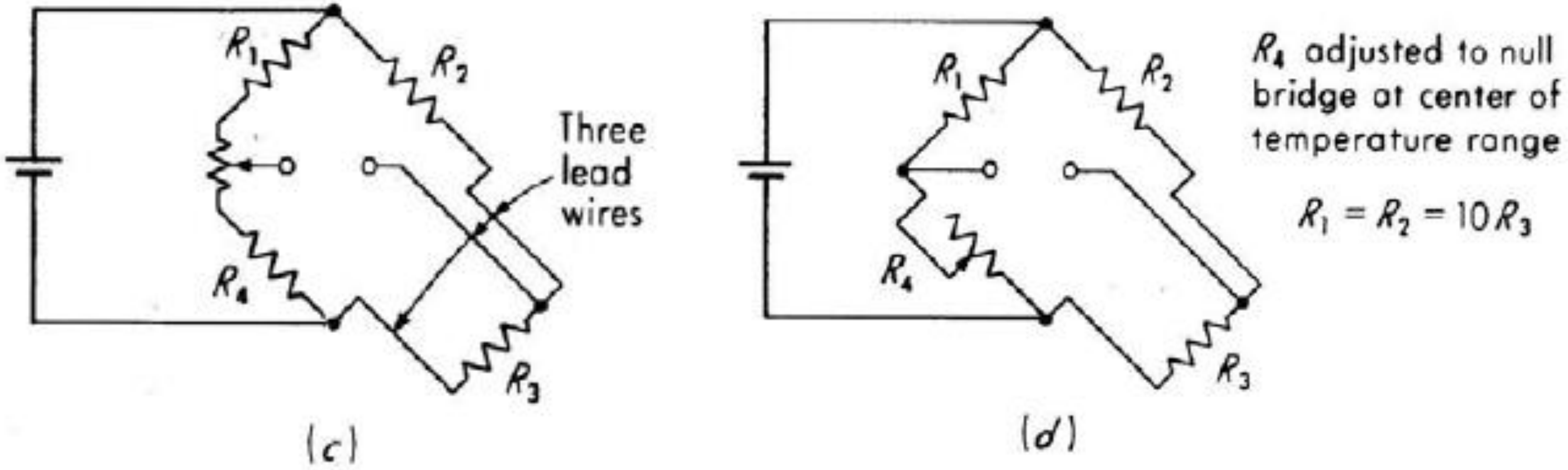


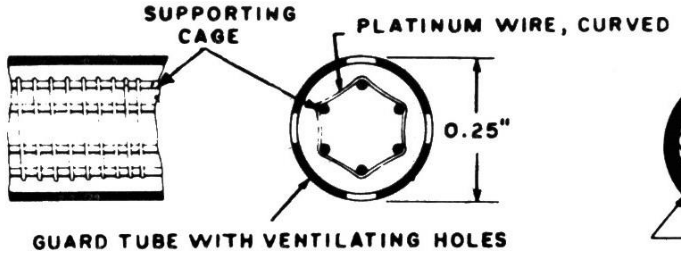
Four-wire ohmmeter technique.

Industrial circuit:

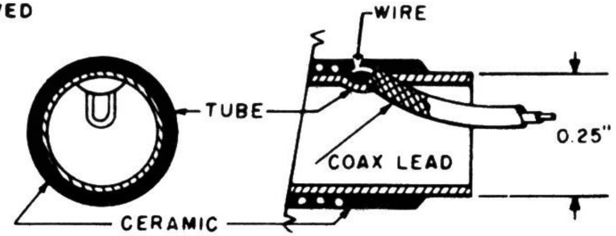


Conceptual circuits:

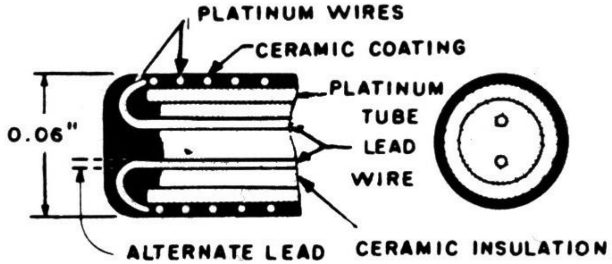




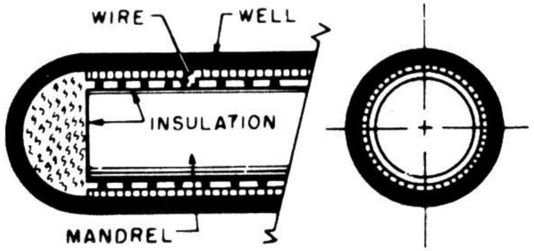
Open-Wire Element



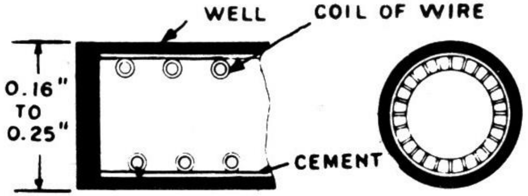
Ceramic Coated Element



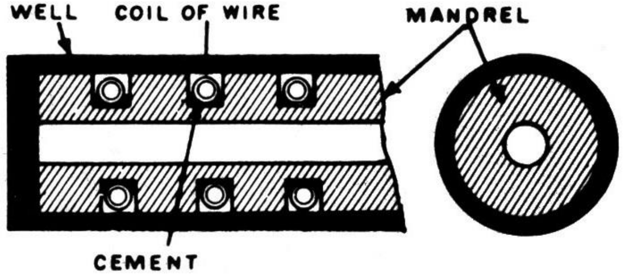
Miniature Ceramic Coated Element



Well-Type Element

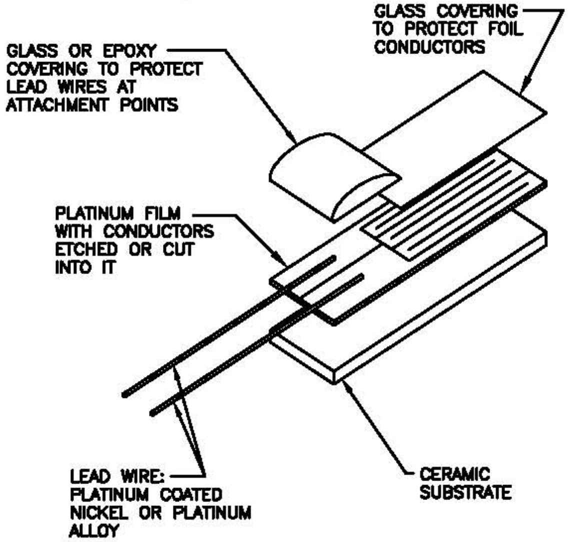


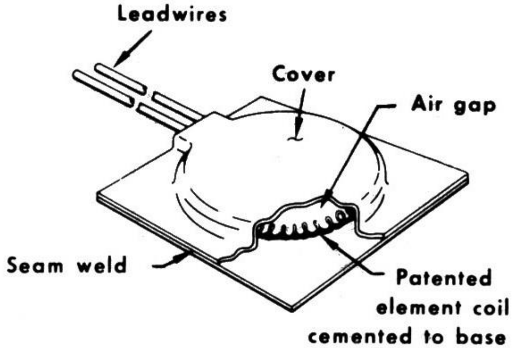
Fast Response Well-Type Element



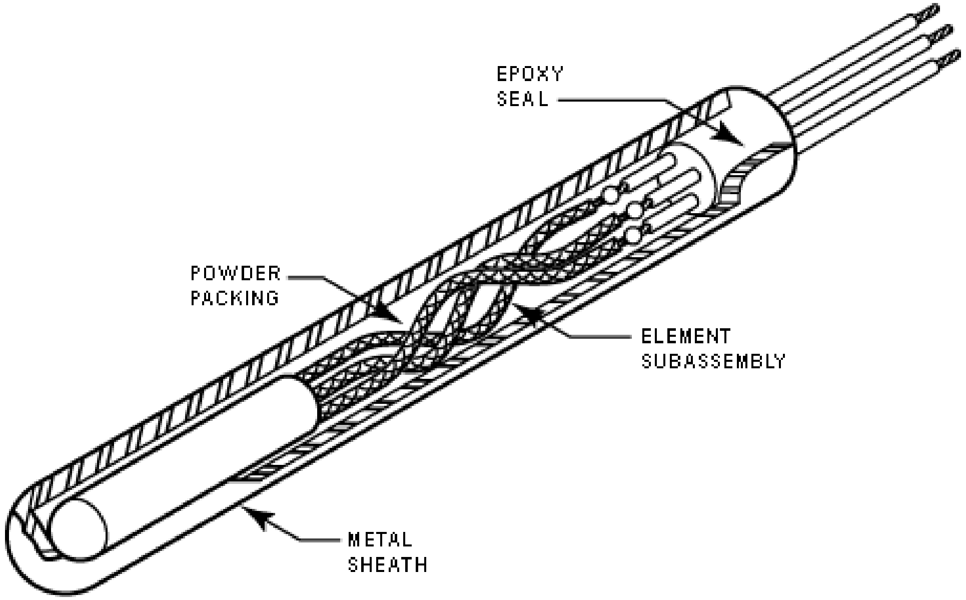
Rugged Well-Type Element

(*a*)





(*b*)

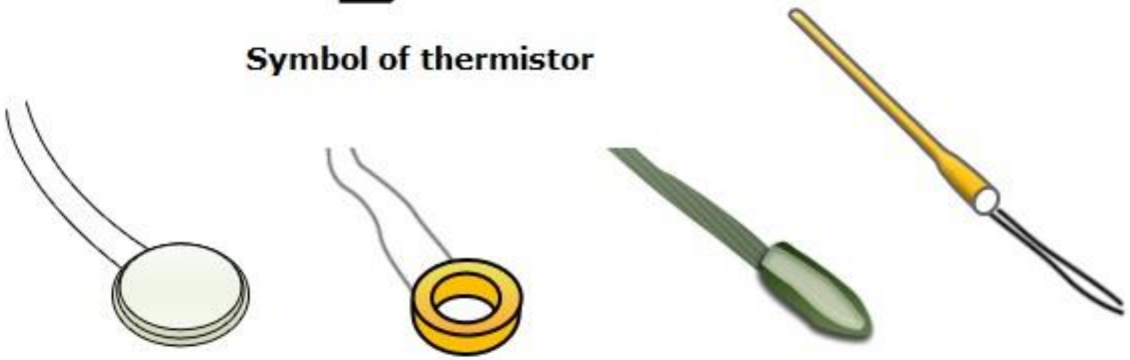


Resistance temperature detector (RTD) construction. (*Courtesy Rosemount Engineering,*

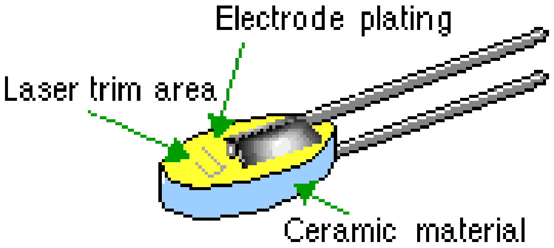
Thermistors :

$$R_T = R_0 \cdot e^{\beta\left(\frac{1}{T}-\frac{1}{T_0}\right)}$$

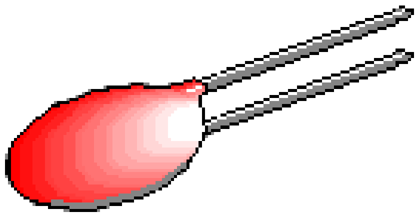
Symbol of thermistor



Different forms of thermistors

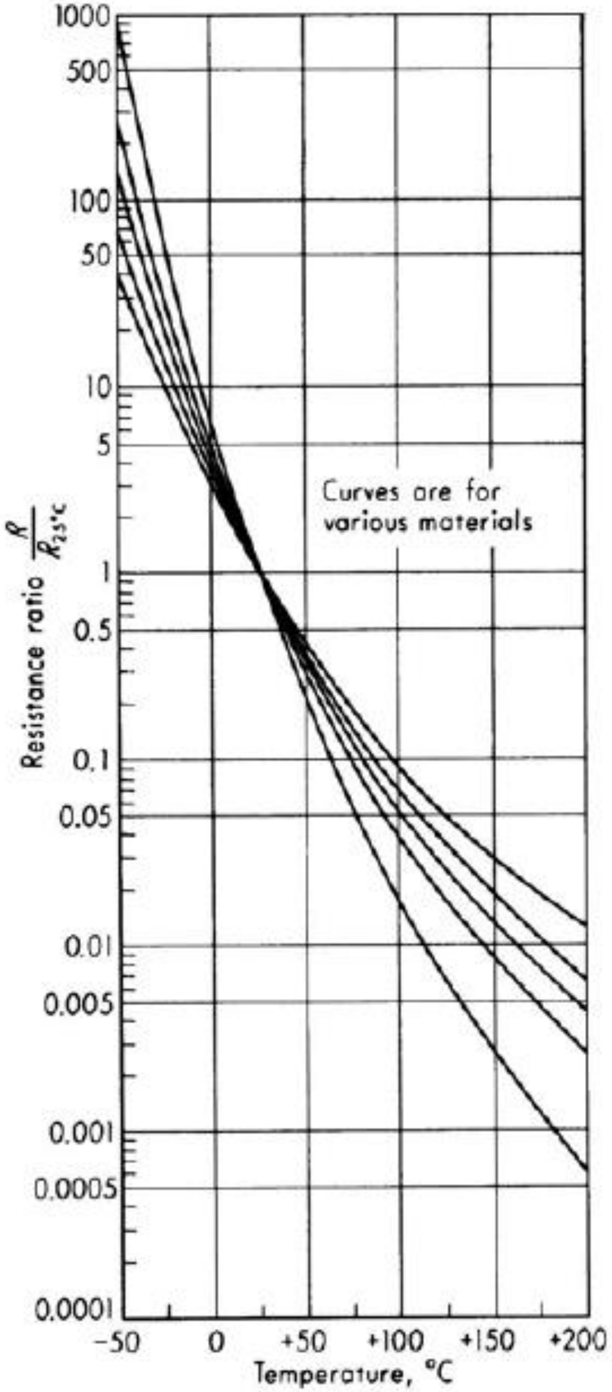


Thermistor without Encapsulation



Thermistor with Encapsulation

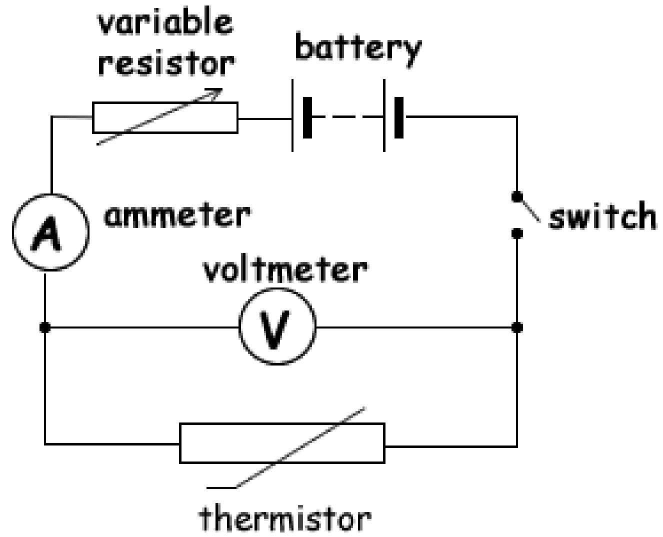
Negative Temperature Coefficient

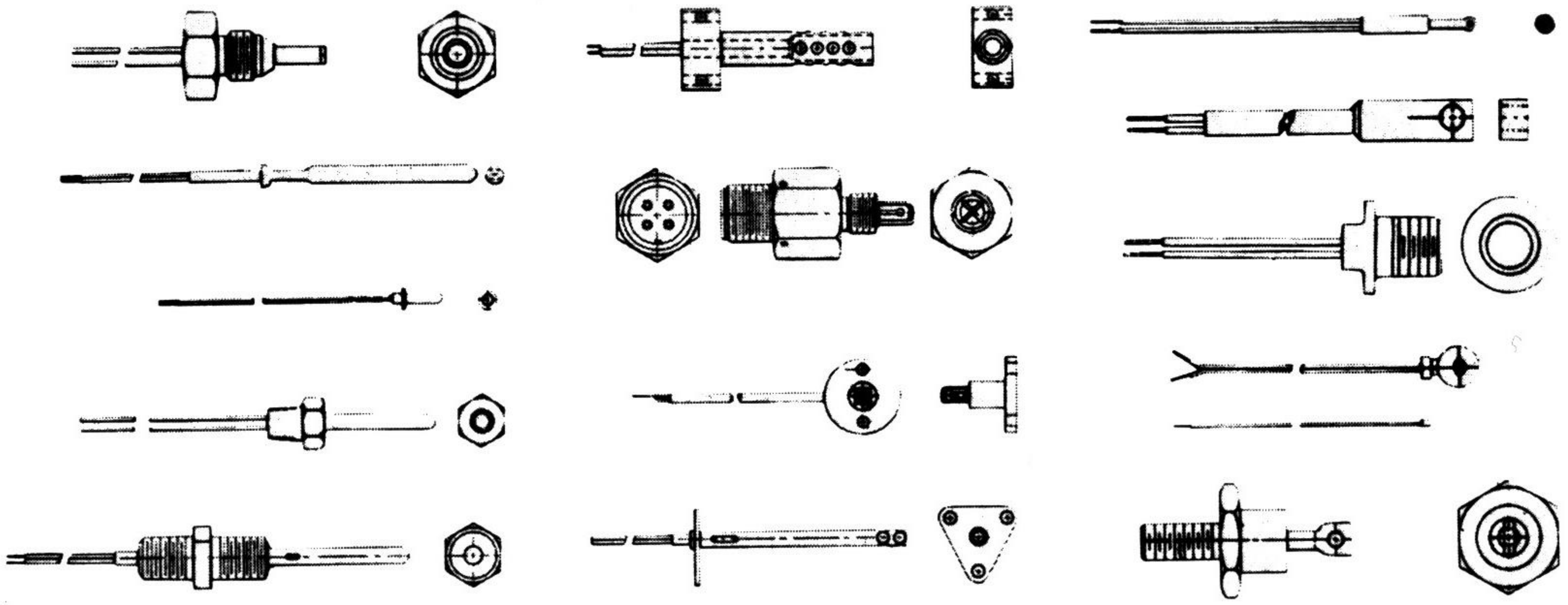


Thermistors: practical examples …

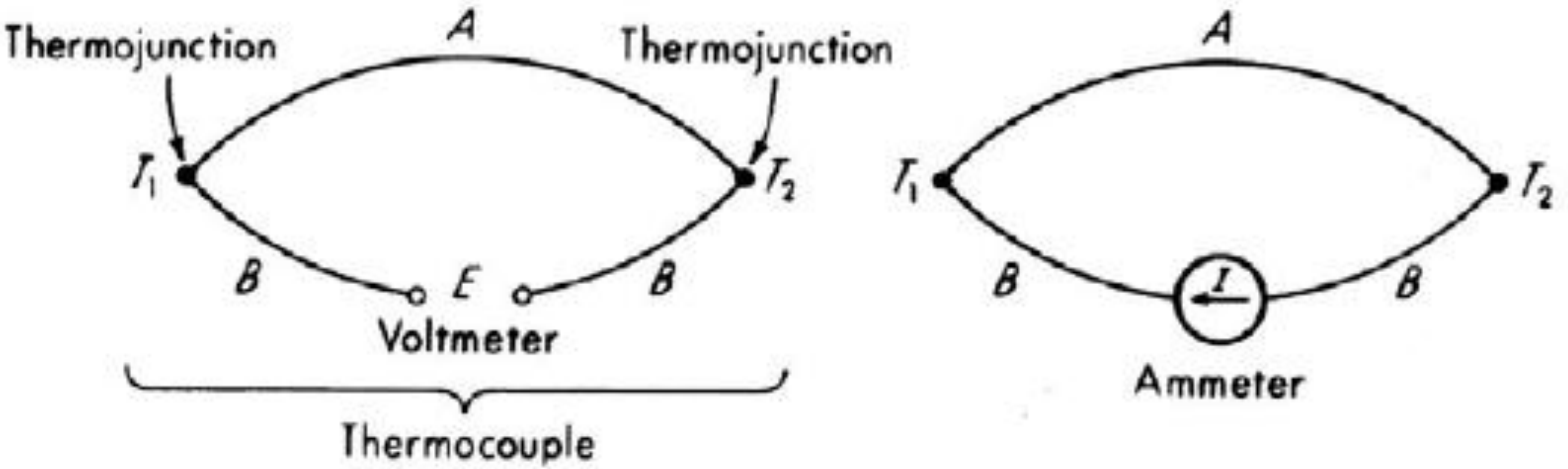
Due to a “fair resistance changes” with temperature, they can be connected to a simple ohmmeter.

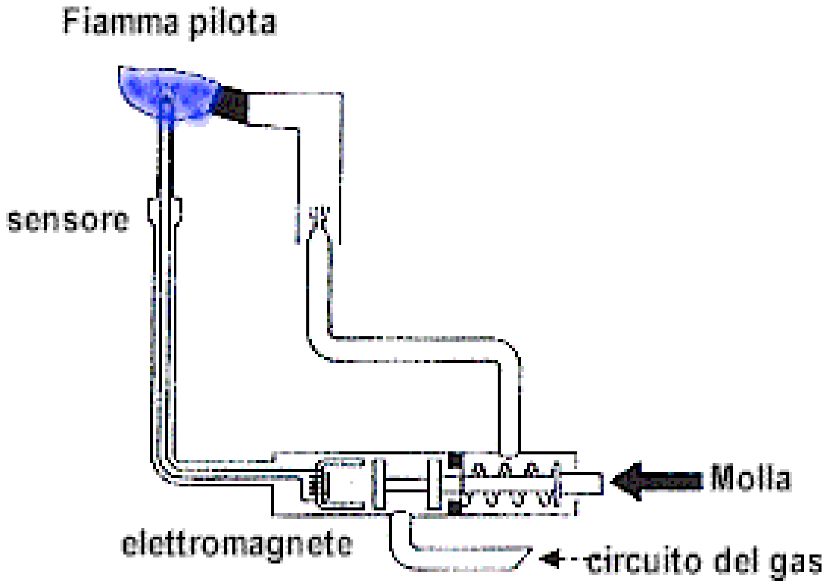
Positive Temperature Coefficient

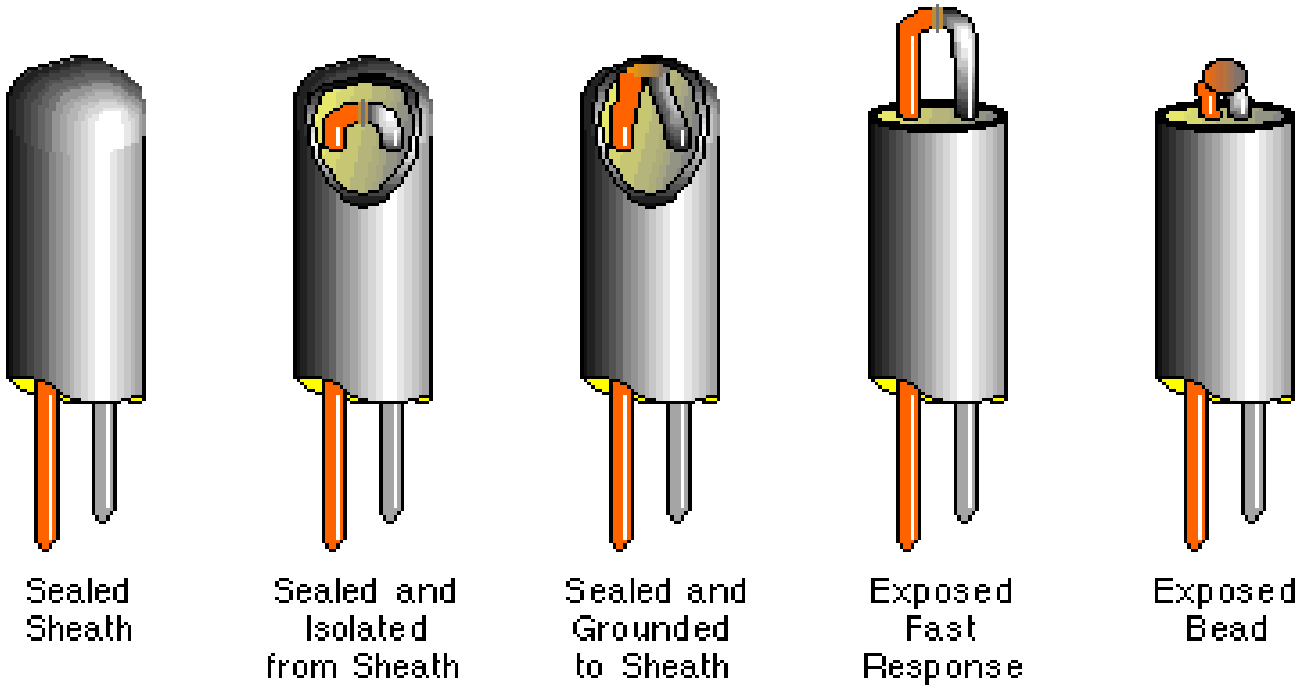




Thermocouples :

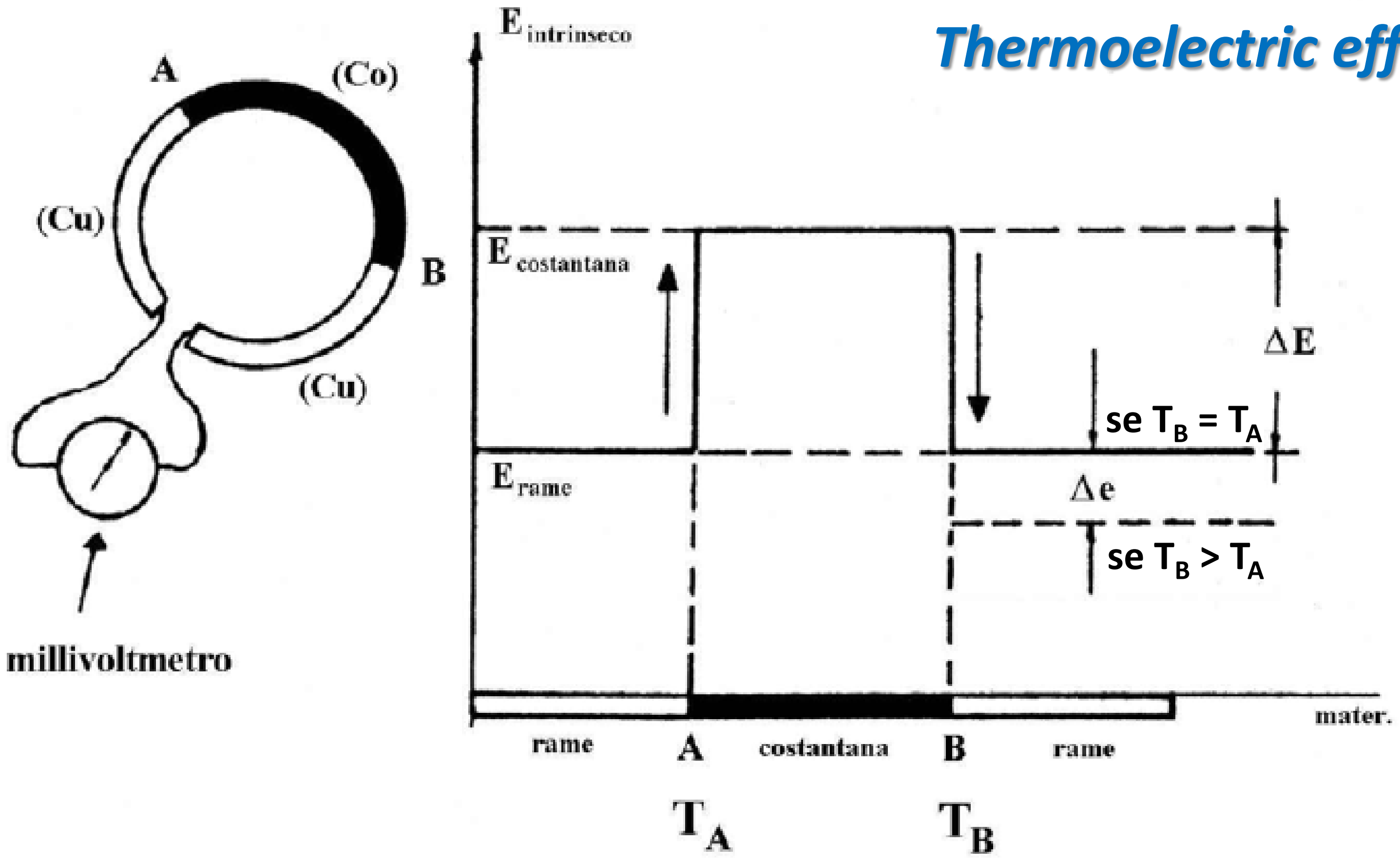






Thermocouple Sheath Options

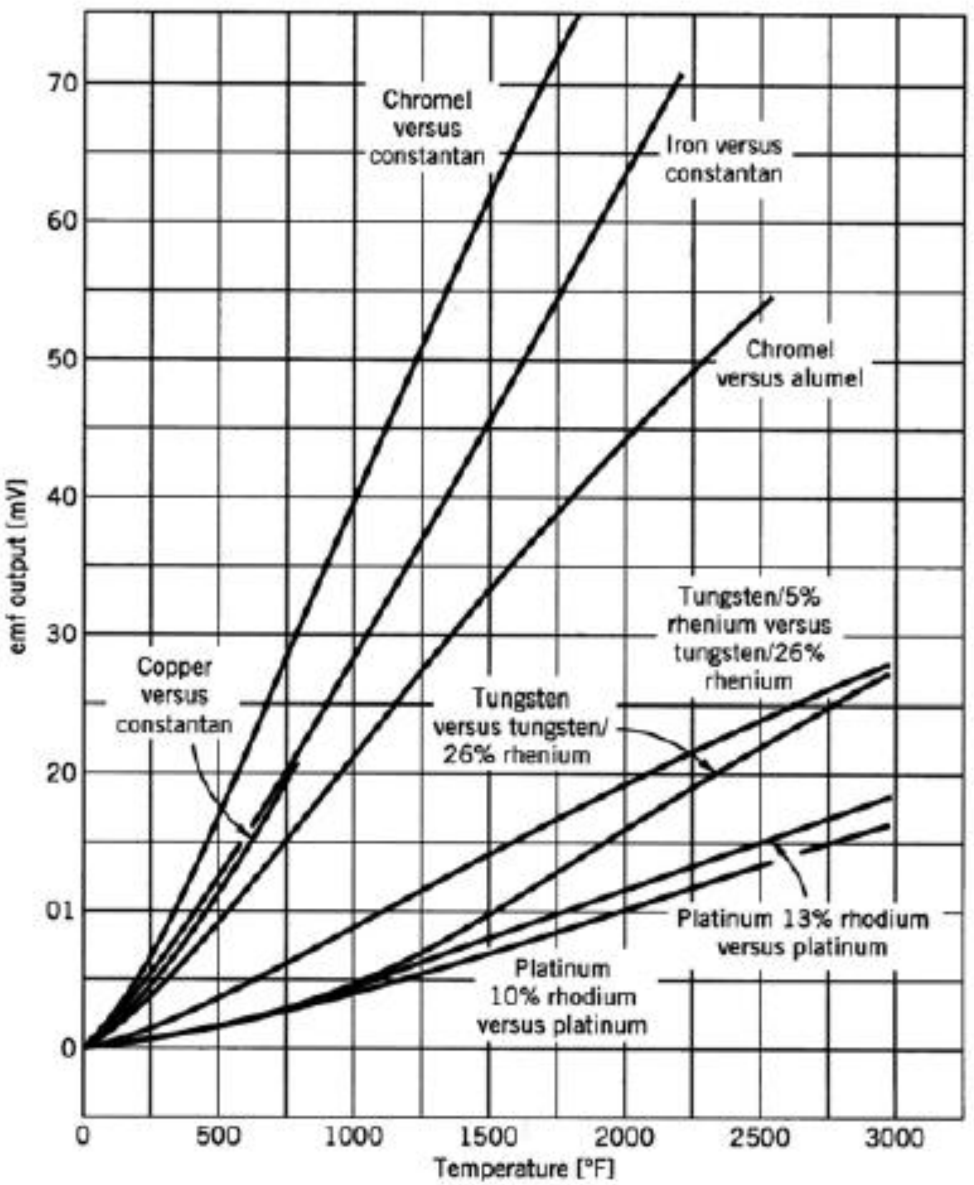
Thermoelectric effects :



SEEBEK effect: *at the junctions of two isothermal metallic materials a potential difference is established. This is the main effect, and it is also the one that originates the Δe when the two junctions are not at the same temperature.*

PELTIER effect: *if in the circuit of the thermocouple the junctions are at temperature $T_B > T_A$, then with $\Delta e \neq 0$, and the circulation of electric current is allowed, this tends to re-establish the thermal equilibrium, cooling the joint B at a higher temperature and heating the joint A at lower temperature.*

THOMSON effect: *if a conductor is not isothermal, a potential gradient appears on it.*



Thermocouple voltage output as a function of temperature for some common thermocouple materials. Reference junction is at 0°C. (From R. P. Benedict, *Fundamentals of Temperature, Pressure and Flow Measurements*, 3d ed., Wiley, New York, 1984)

Standard Thermocouple Compositions[a]

Type	Wire: Positive	Wire: Negative	Expected Bias Error[b]
S	Platinum	Platinum/ 10% rhodium	±1.5°C or 0.25%
R	Platinum	Platinum/ 13% rhodium	±1.5°C
B	Platinum/ 30% rhodium	Platinum/ 6% rhodium	±0.5%
T	Copper	Constantan	±1.0°C or 0.75%
J	Iron	Constantan	±2.2°C or 0.75%
K	Chromel	Alumel	±2.2°C or 0.75%
E	Chromel	Constantan	±1.7°C or 0.5%

Alloy Designations

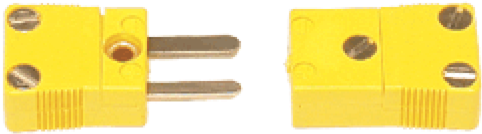
Constantan: 55% copper with 45% nickel

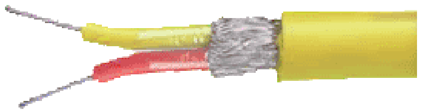
Chromel: 90% nickel with 10% chromium

Alumel: 94% nickel with 3% manganese, 2% aluminum, and 1% silicon

[a] From Temperature Measurement ANSI PTC 19.3-1974.

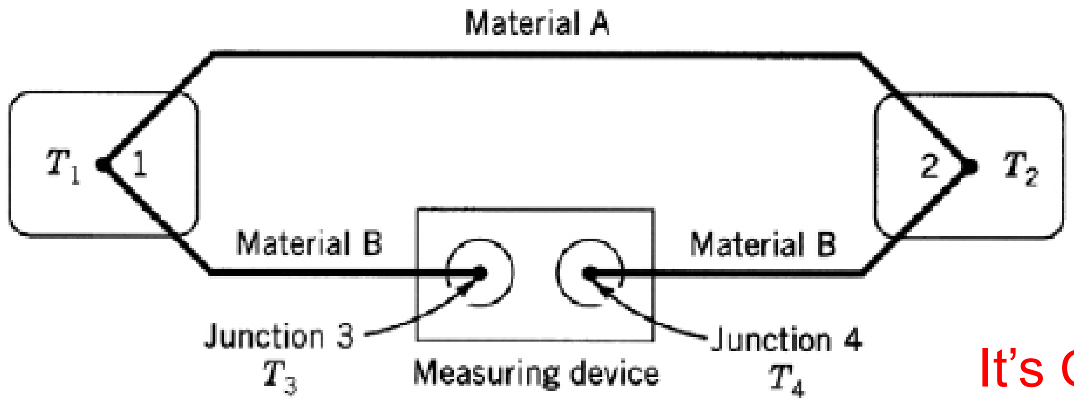
[b] Use greater value; these limits of error do not include installation errors.

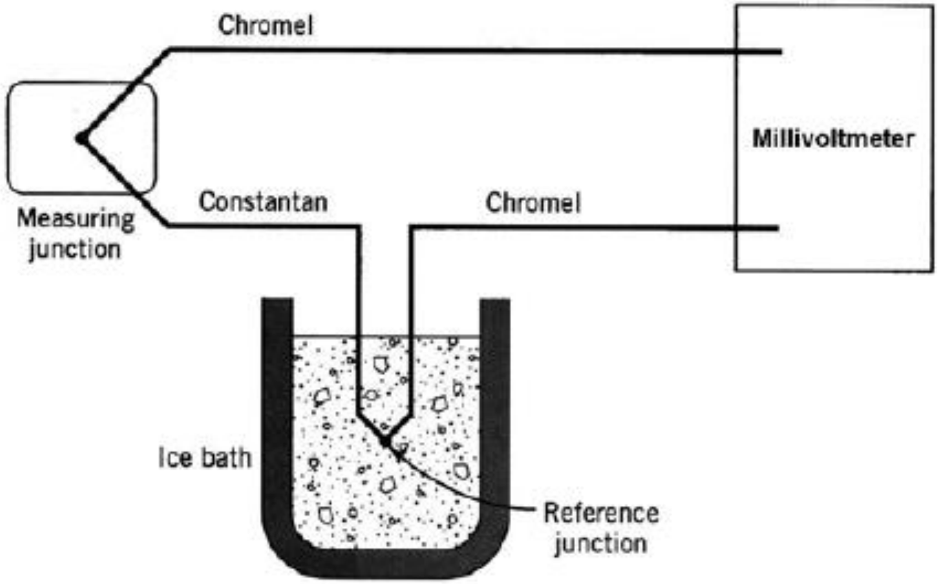




Circuital connections:

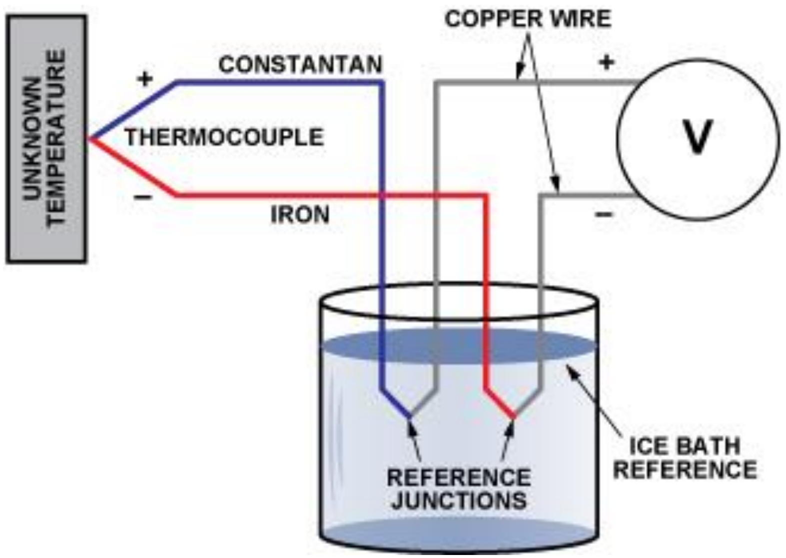
Rule of the ***intermediate metals***

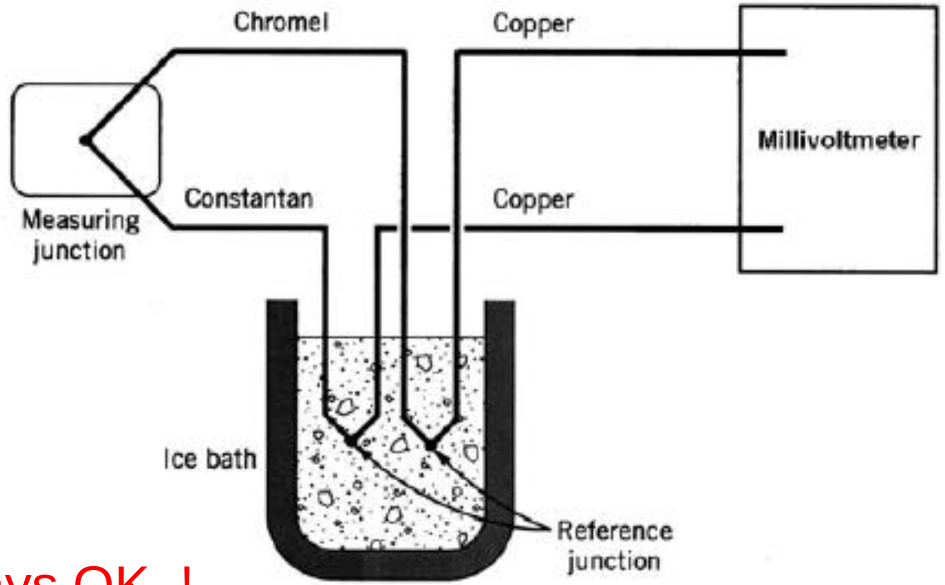




(a)

It's OK only if $T_3 = T_4$



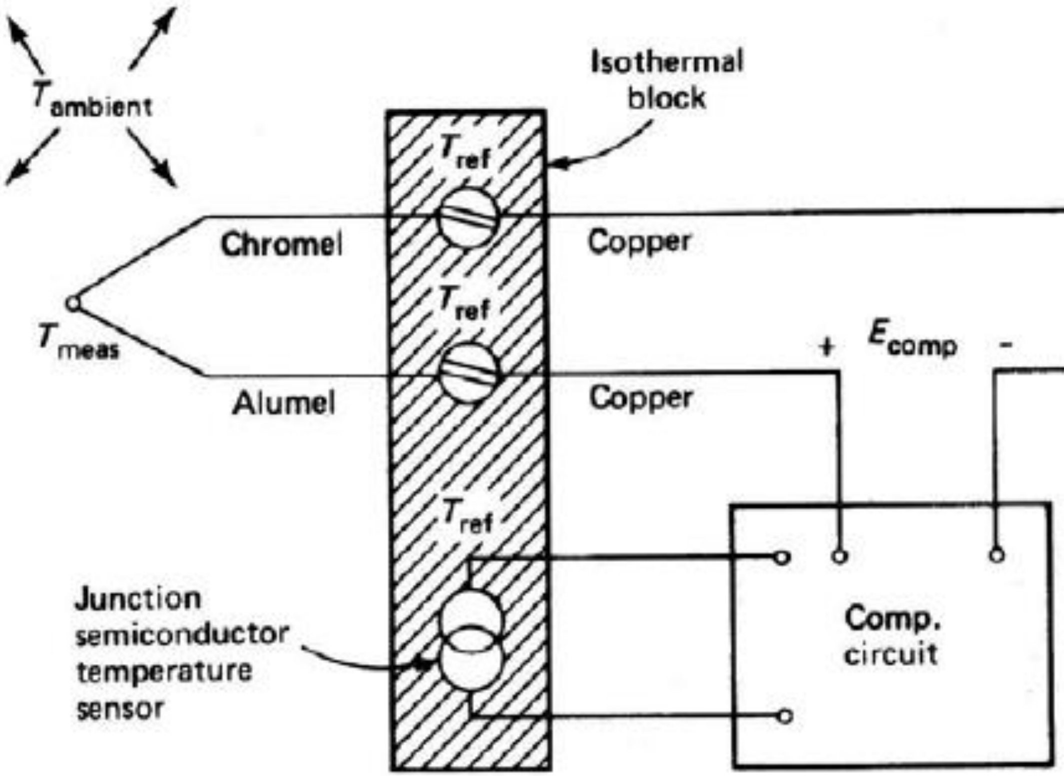


(b)

it's always OK !

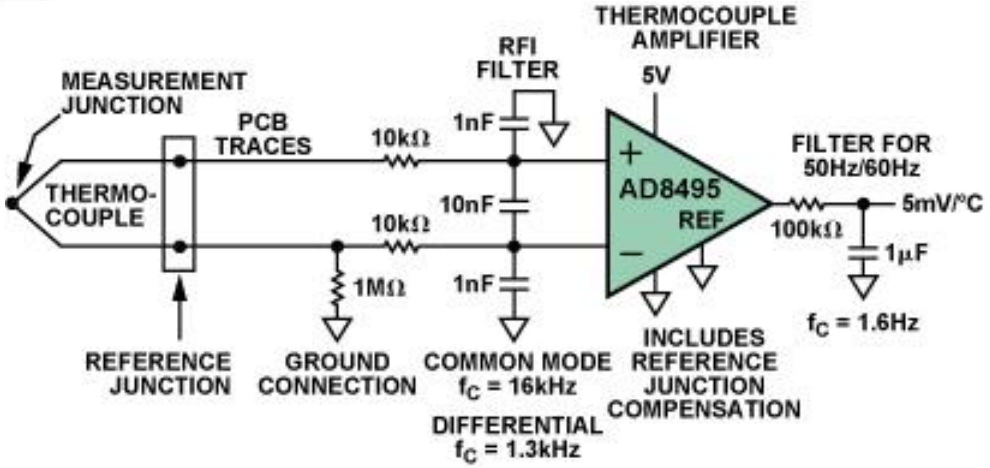
Thermocouple with ***electronic junction*** (with reference temperature T_a different from 0°C)

Rule of the ***intermediate temperatures***



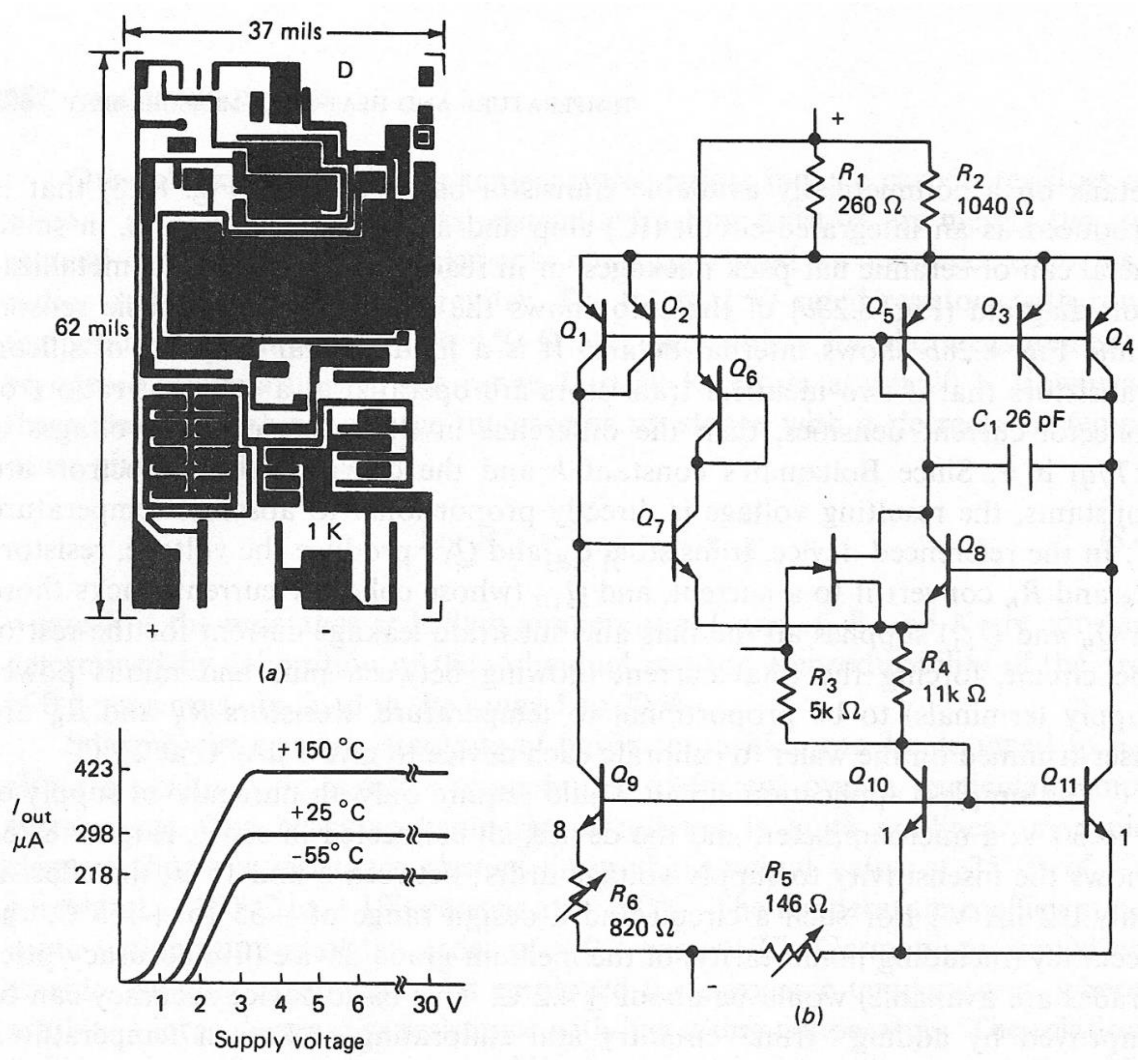
Isothermal block reference-junction technique.

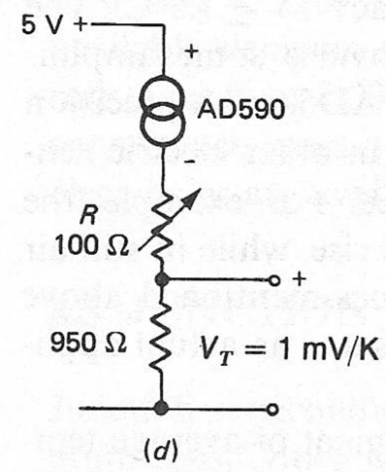
Commercial realization:

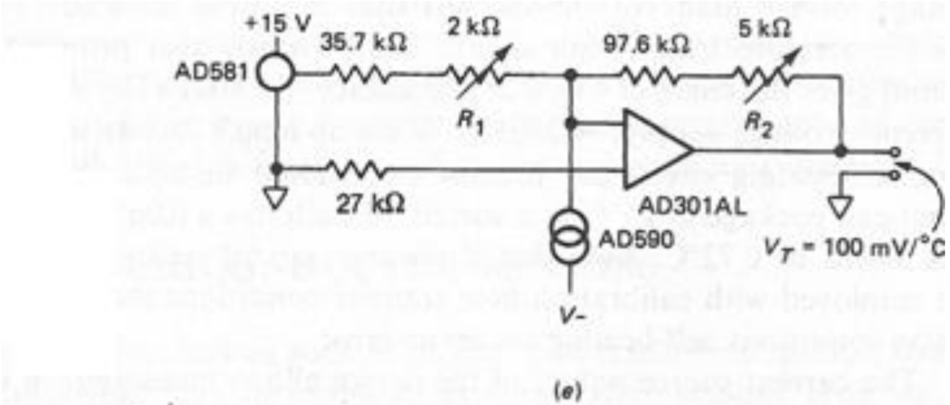


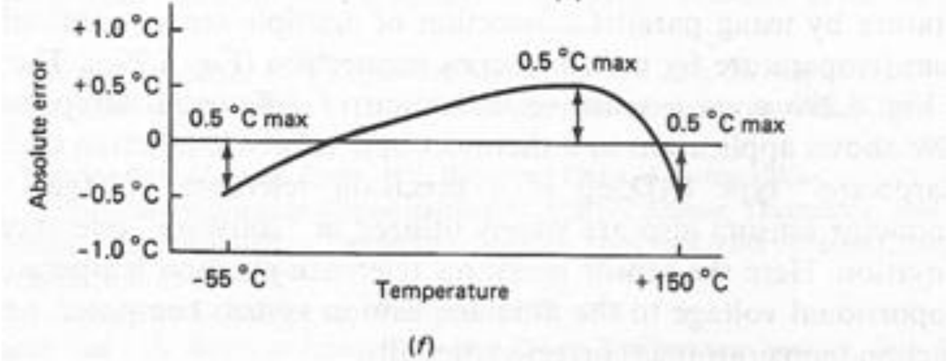
if $T_{ref} = T_a \neq T_0 = 0\,°C$ the thermocouple detects $\Delta e \propto T_x - T_a$ that can not be interpreted directly on the tables ! The semiconductor thermometer measures $T_{ref} = T_a$, the compensation circuit processes the $E_{comp} \propto T_a - T_0$ and adds it to the Δe produced by the thermocouple. The voltmeter receives the compensated voltage $E = \Delta e + E_{comp}$ that can be interpreted on the thermocouple tables.

Electronic semiconductor temperature sensor:







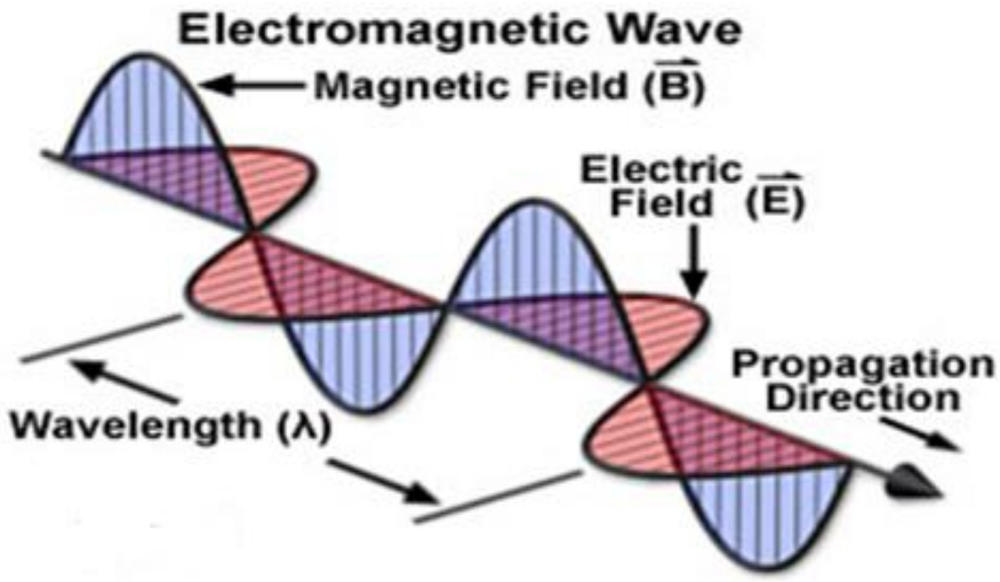


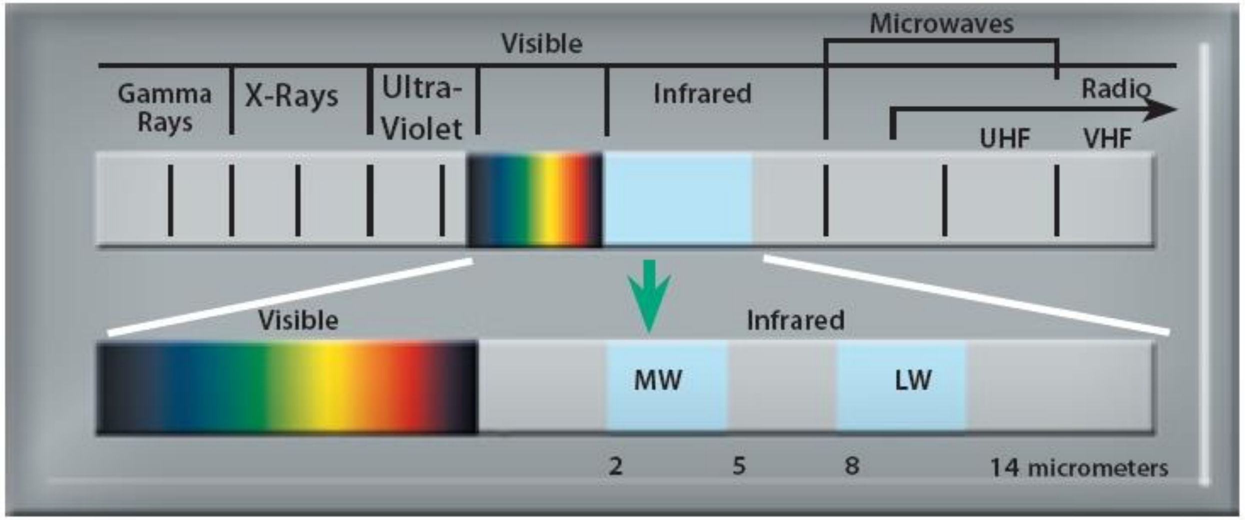
For all those situations in which the contact between the physical phenomenon and thermometer is NOT possible:

RADIATION thermometers

The ***thermal radiation of a body*** originates by **thermal agitation of it's atoms** but, outside the body, it is nothing more than a regular ***electromagnetic radiation*** with a **wavelength between 0,3 e 40 µm**.

The spectrum of *visible radiation* is with a wavelength **from 0.1 to less than 1 micron** therefore, a large part of the thermal radiation lies in the ***infrared***.
The bodies with an ***ideal thermal radiation*** are the **blacks bodies**, as they completely absorb the radiation hitting them and, at a given temperature, they emit the highest amount of heat radiation.



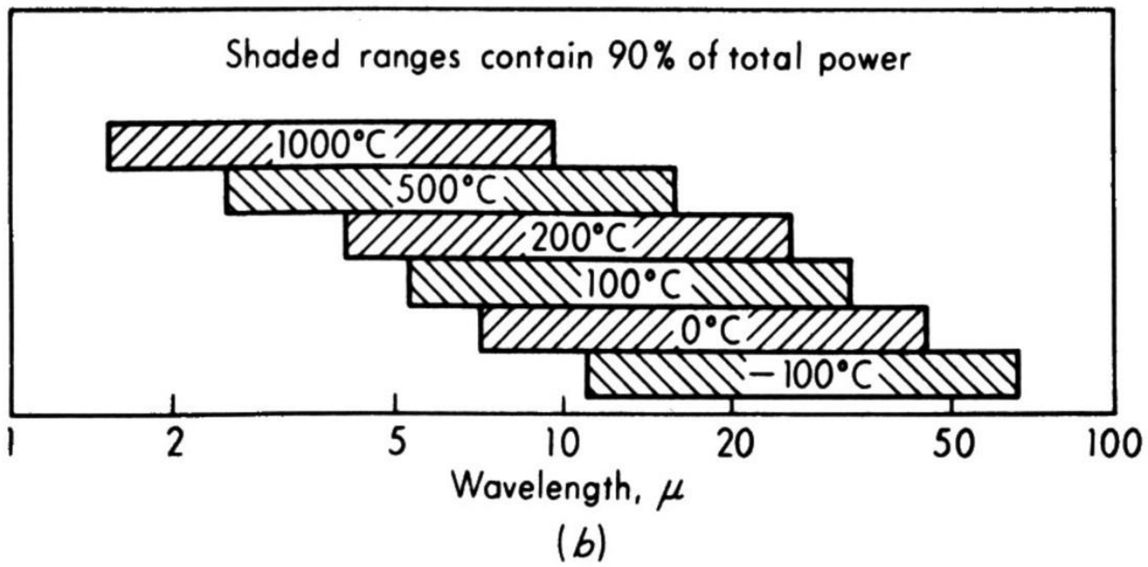


The physical law that describes this phenomenon is the **Planck 's law** :

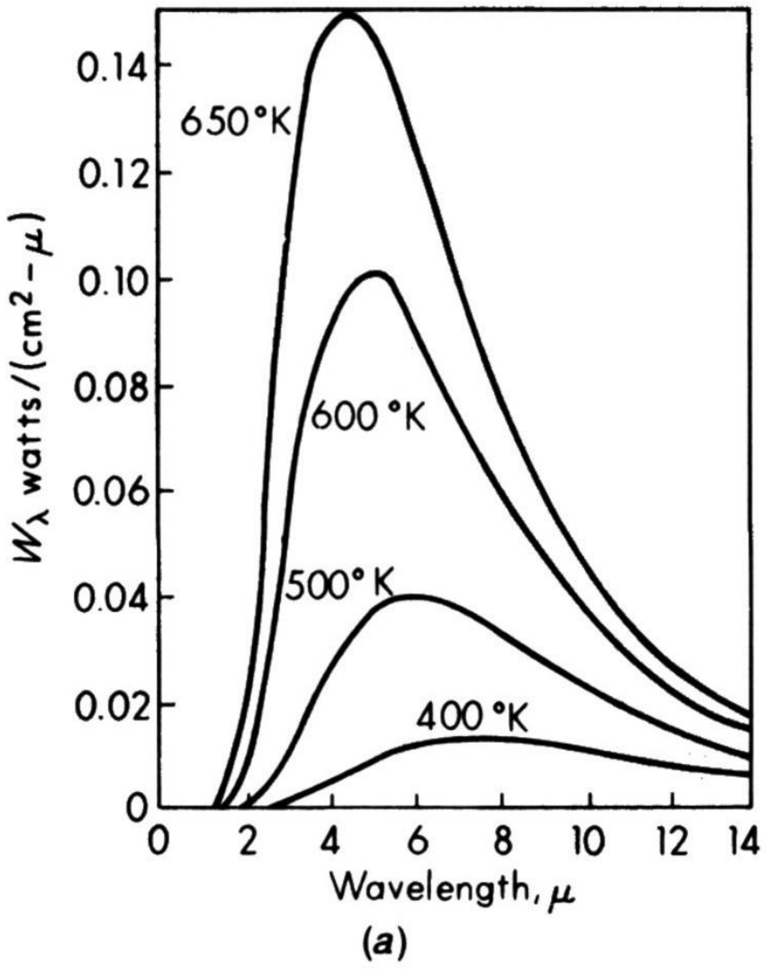
$$L_\lambda = \frac{C_1}{\lambda^5\left(e^{\frac{C_2}{\lambda T}} - 1\right)} \quad \left[\frac{W}{m^2 m sr}\right]$$

which provides the ***spectral radiation level*** $\boldsymbol{L_\lambda}$ as a function of the ***wavelength*** $\boldsymbol{\lambda}$ of the radiation and of the ***absolute temperature T*** of the black body.

The figure shows a representation of the law for several values of T : with increasing T the ***radiance*** $\boldsymbol{L_\lambda}$ increases but shifts to smaller ***wavelengths*** $\boldsymbol{\lambda}$ ...



Blackbody radiation.



The ***real bodies*** behavior differ from the ***black body*** and this fact is reckoned in terms of **emissivity ε** (***dimensionless parameter***):

$$\varepsilon_{\lambda,T} = \frac{L_{\lambda a}}{L_{\lambda}}$$

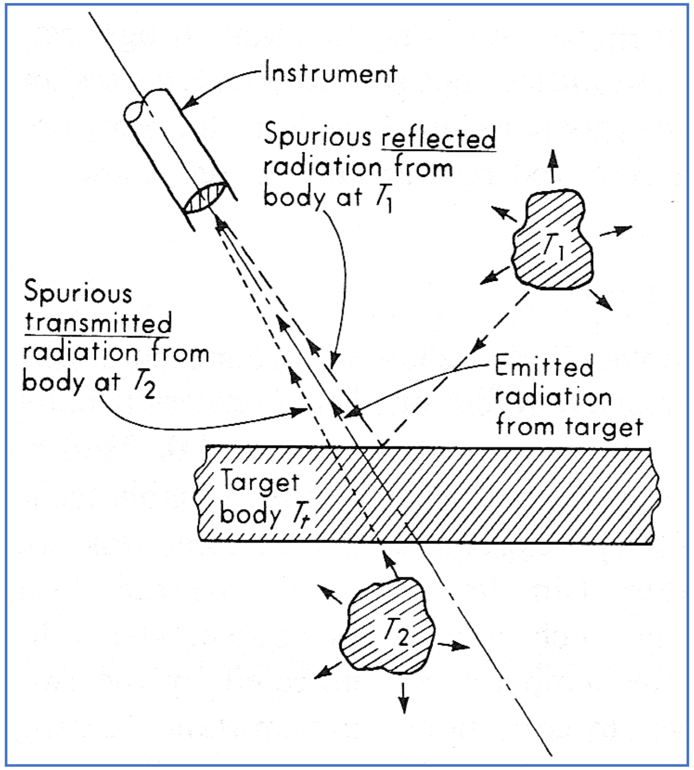
where **L_{λ}** is the ***radiance of the black body*** *and* **$L_{\lambda a}$** the ***radiance of the real body*** at the same temperature T of the black body. Real body radiance therefore can be written as :

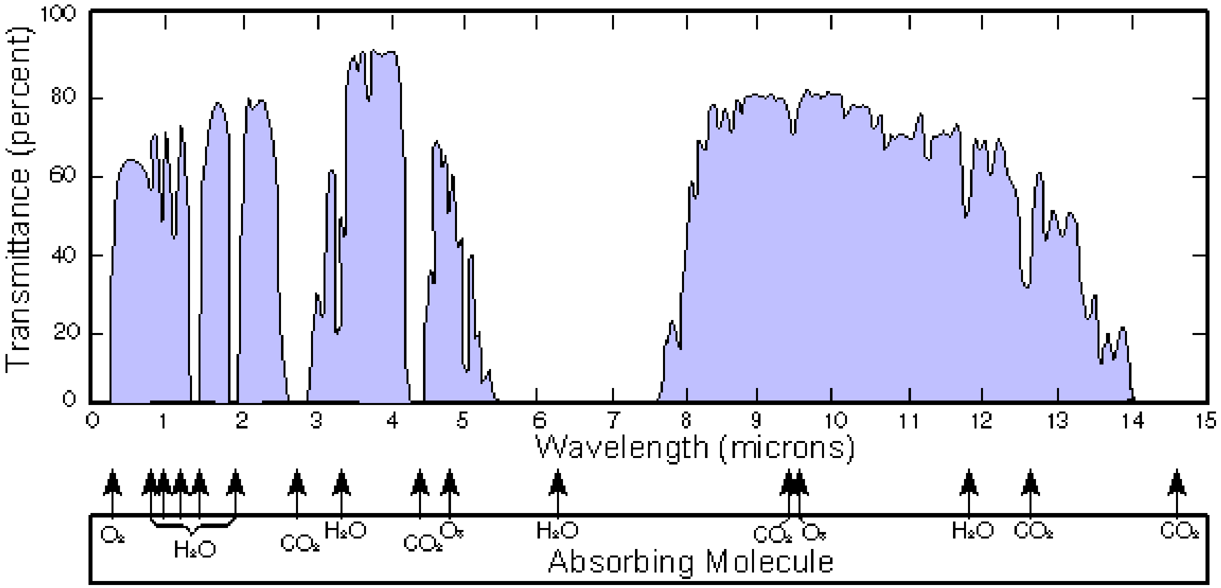
$$L_{\lambda_a} = \frac{C_1 \varepsilon_{\lambda,T}}{\lambda^5 \left(e^{\frac{C_2}{\lambda T}} - 1\right)} \quad \left[\frac{W}{m^2 \times sr}\right]$$

Together with the ***emissivity*** $\boldsymbol{\varepsilon}$ other two parameters are also considered: the ***reflectance*** $\boldsymbol{\rho}$ and ***transmittance*** $\boldsymbol{\theta}$ of surrounding bodies. If the body is in thermal equilibrium, the radiated energy is equal to the energy absorbed and we can write the following relationship :

$$\varepsilon + \rho + \theta = 1$$

Then we must also take into account the *losses due to air or dust along the optical path*, the *object's size* and its *distance from the thermometer* (area length error) …





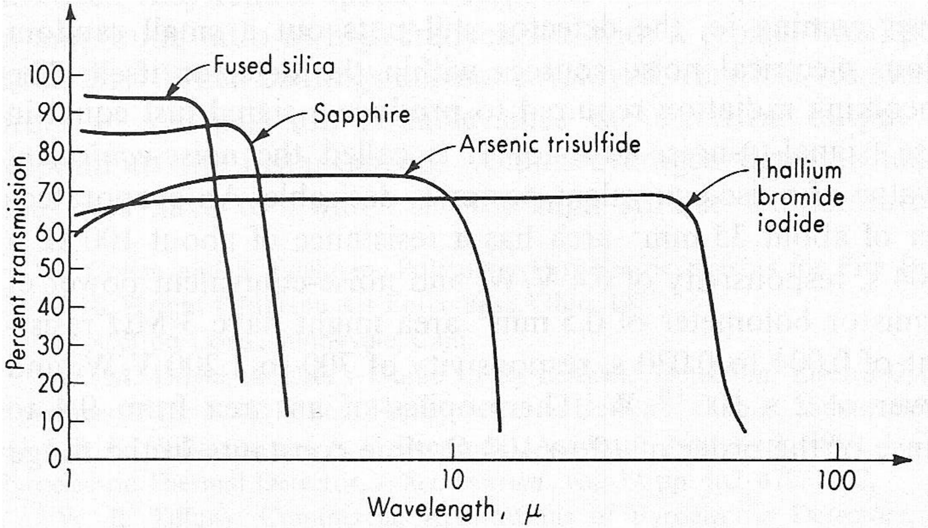
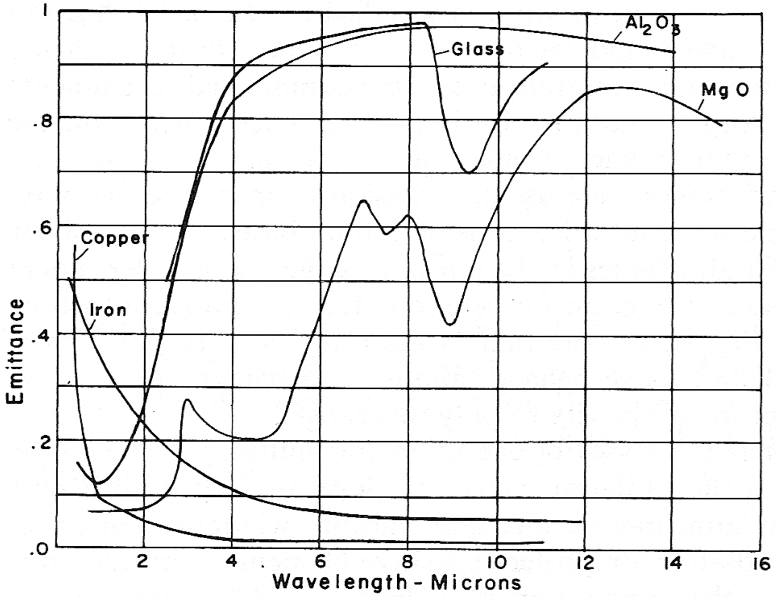


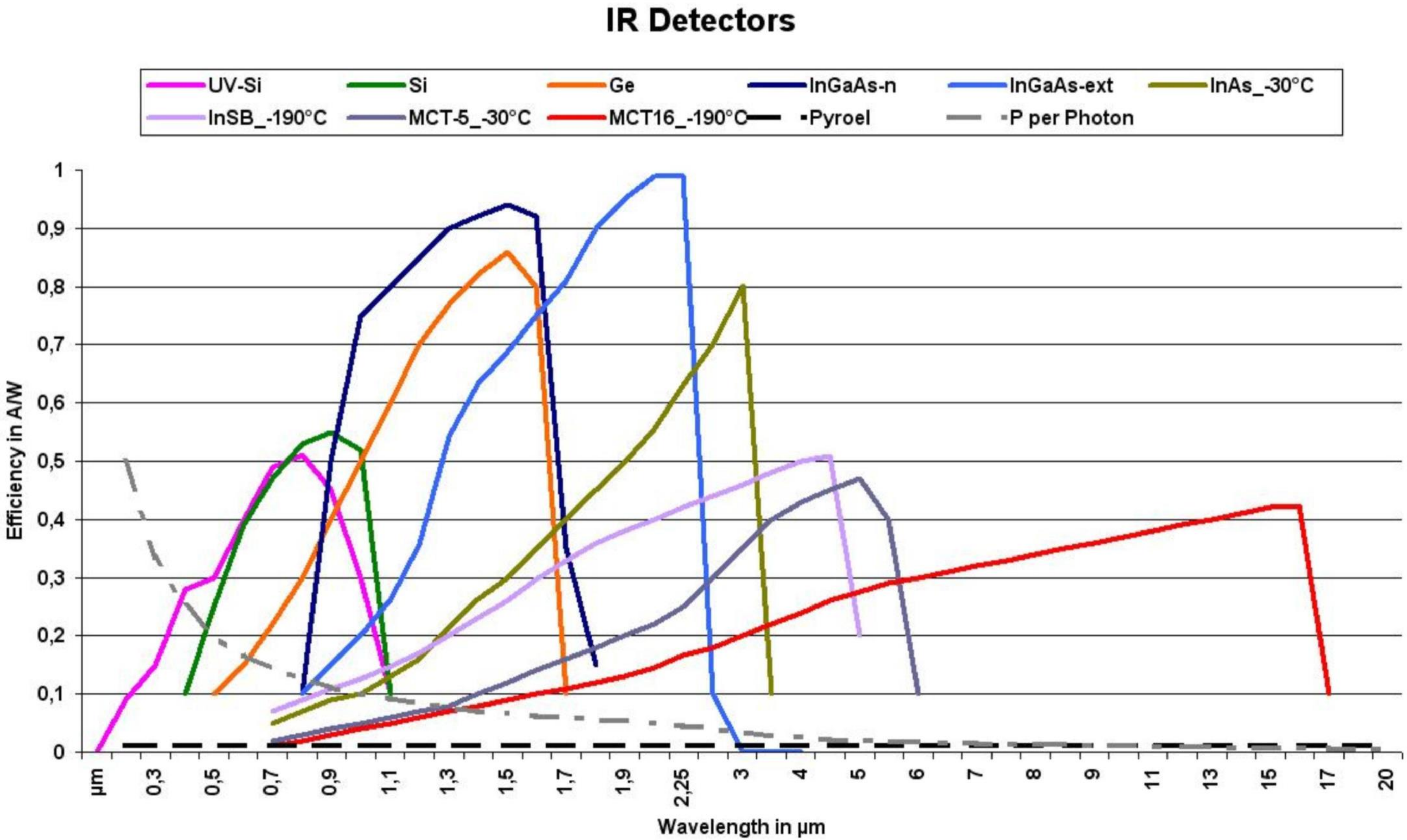
Figure 8.34 Spectral transmission of optical material.

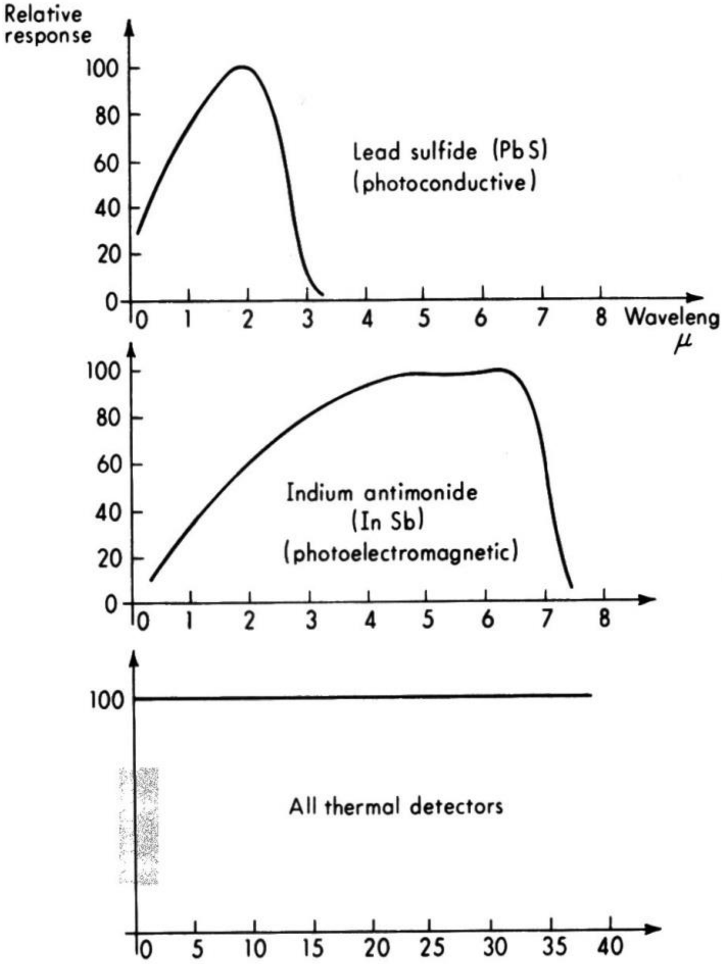


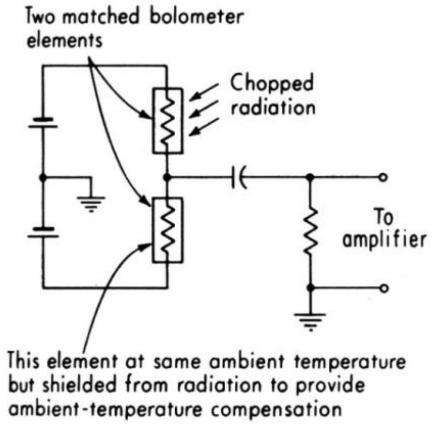
(b)

Figure 8.31 Measurement problems with reflective/translucent targets; emittance of real materials.

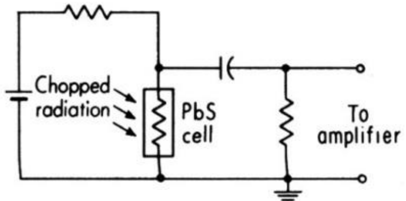
The detectors are divided into ***thermal detectors*** (bolometers) and ***photodetectors*** (pyrometers)



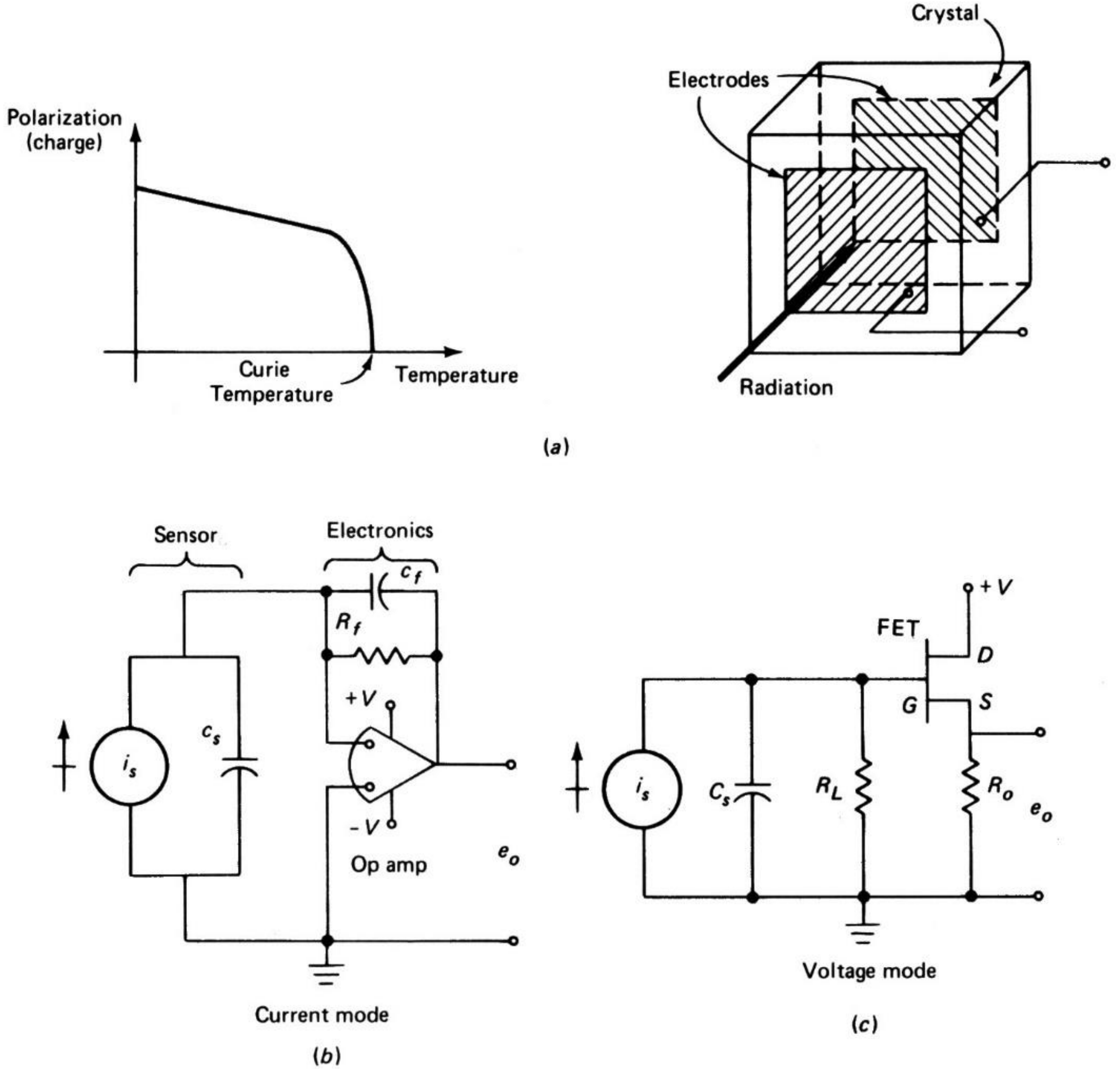




Simple circuit for a high-resistance bolometer



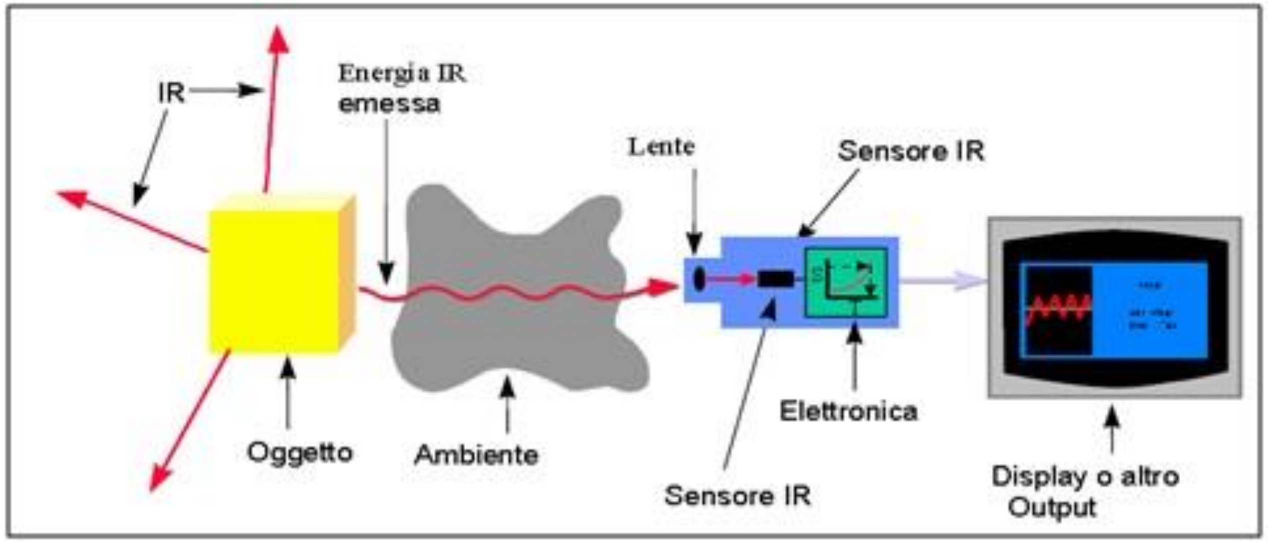
Simple circuit for a lead sulfide cell



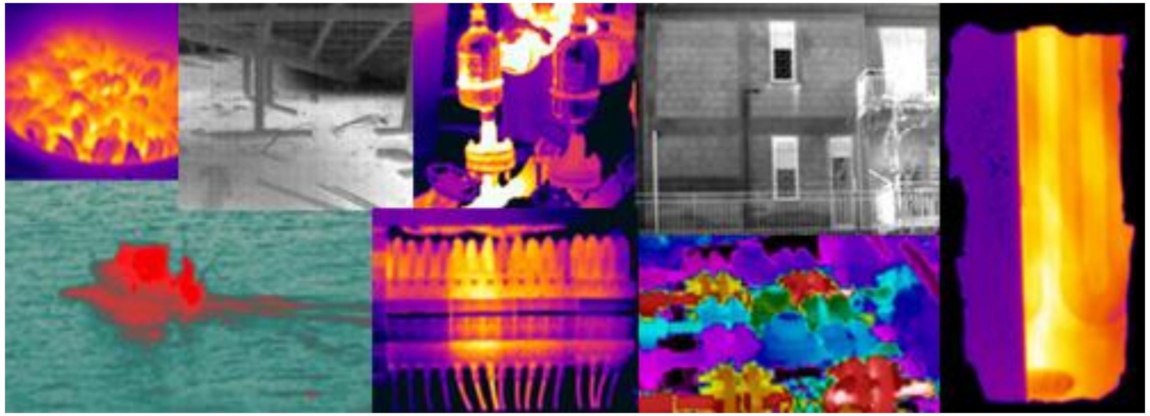
Pyroelectric detector and electronics.

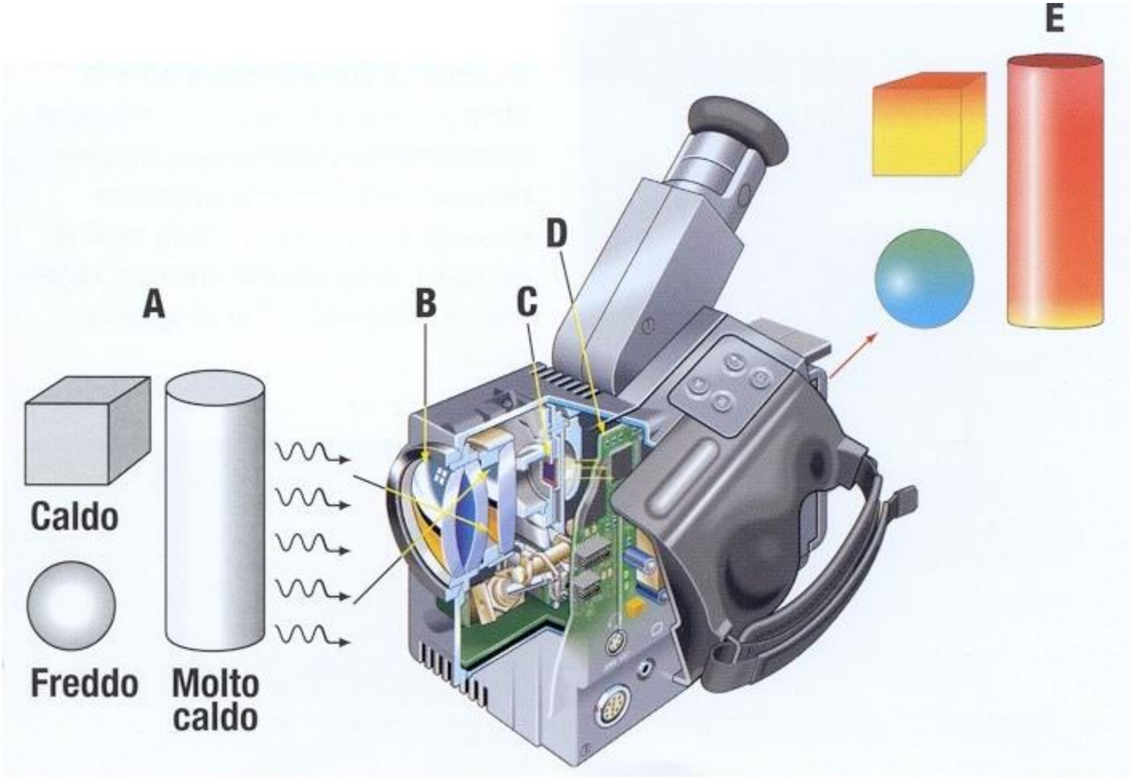
THERMOGRAPHY :

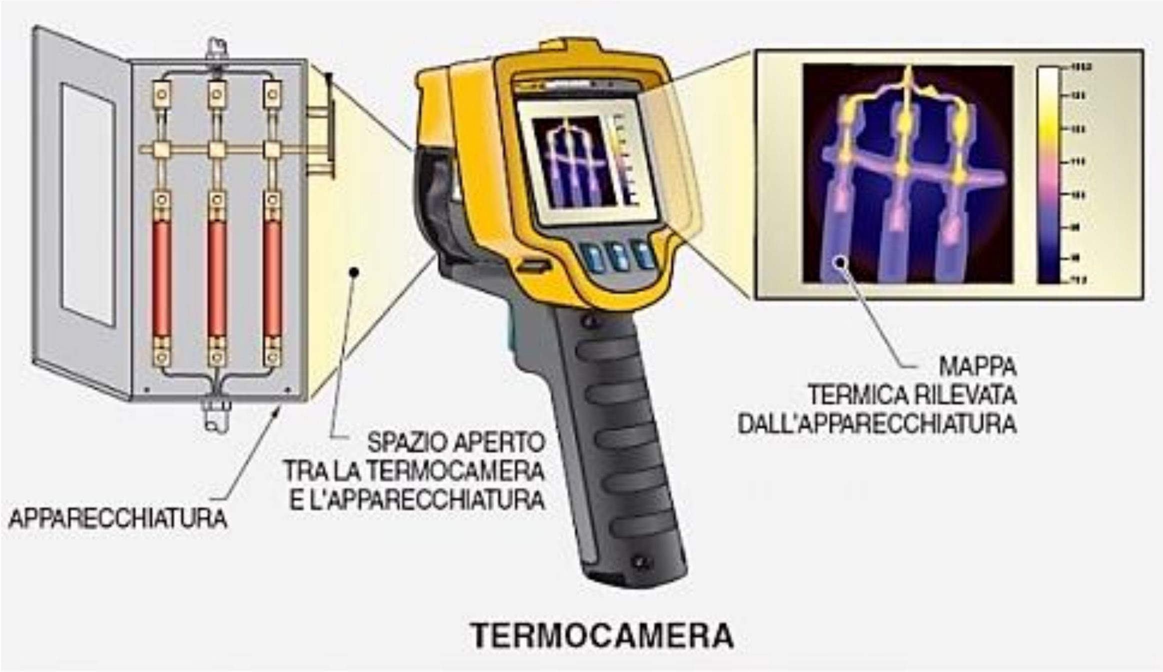
The cameras are all *individually calibrated* by comparison with a black body at a controlled temperature T .
For each pixel of the image, the voltage-temperature characteristic V-T is stored in the LUT memory (Look-Up-Table)

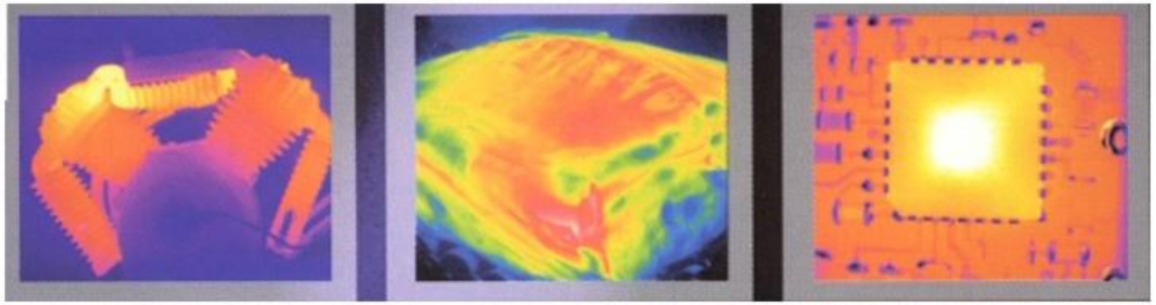


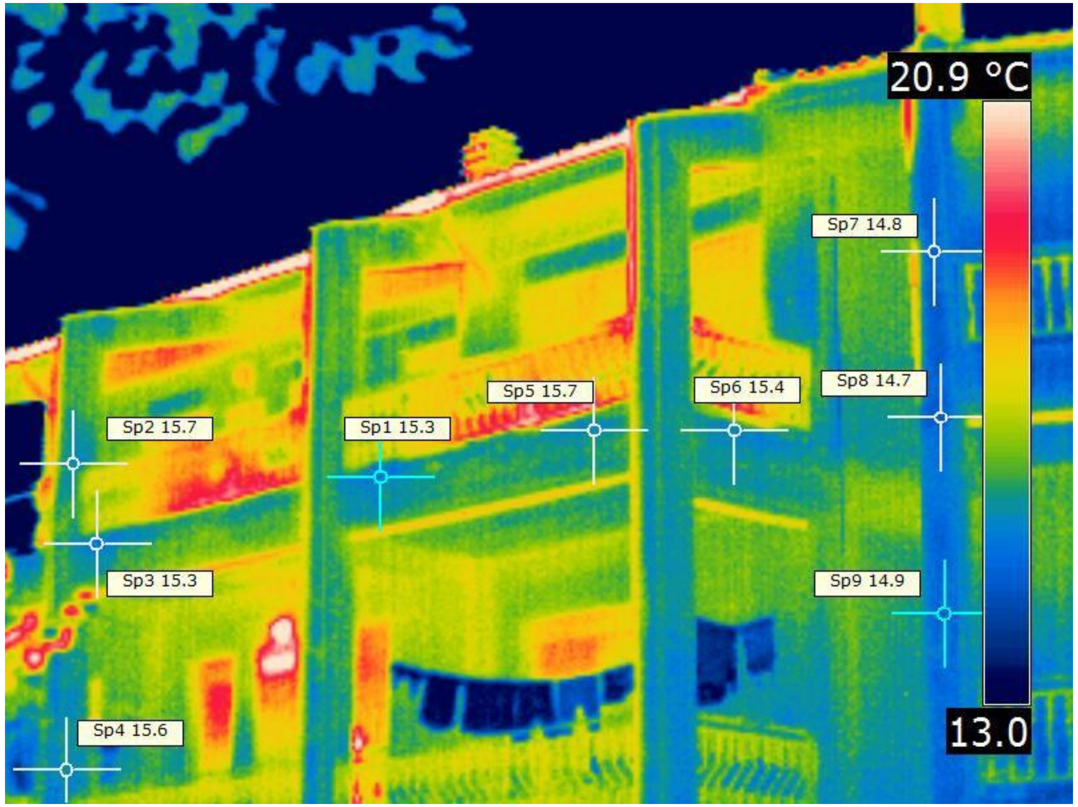
Thermal camcorder :

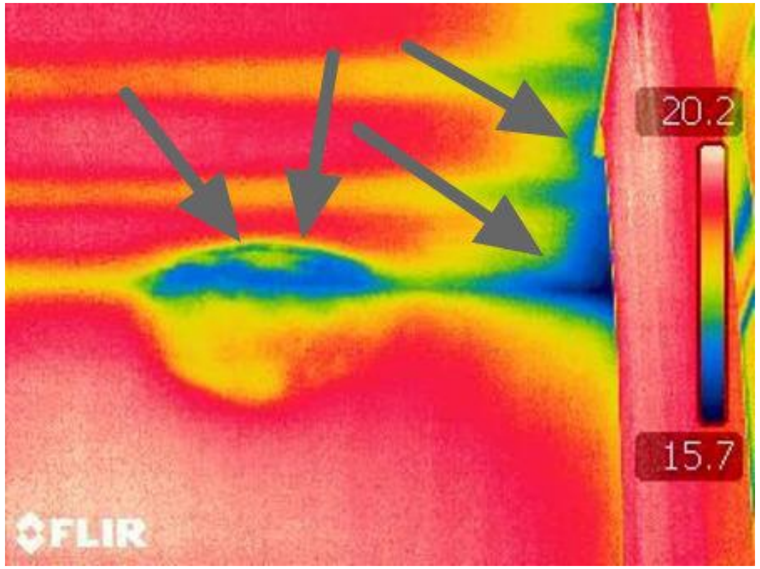


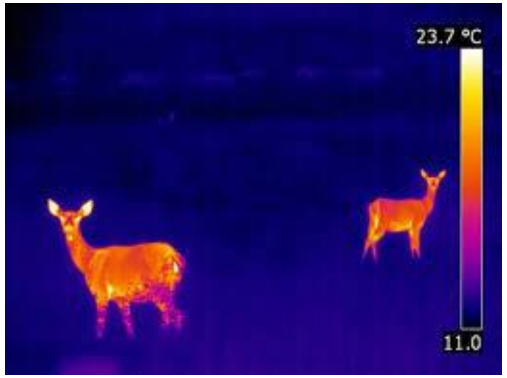


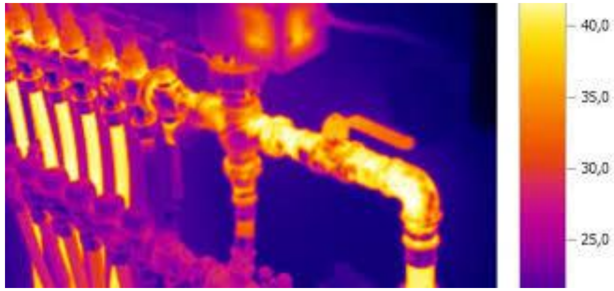


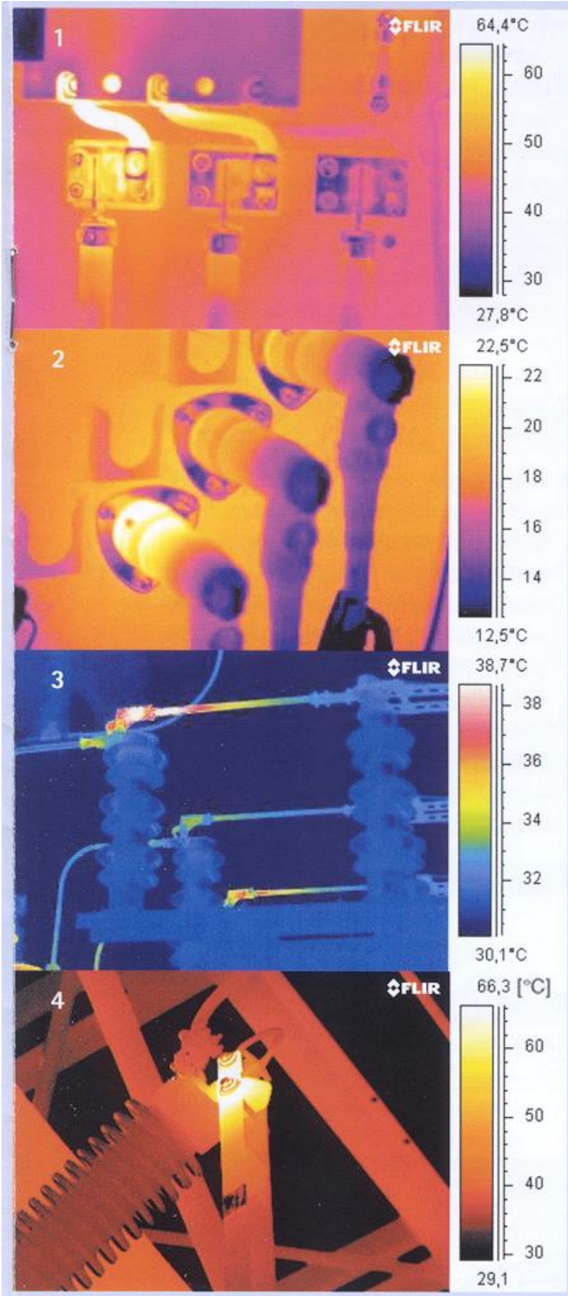












1. Connessione di un fusibile difettosa
2. Connessione allentata
3. Ossidazione di un contatto ad alto voltaggio
4. Connessione effettuata non correttamente