TEMPERATURE MEASUREMENT

AGENDA

A. Introduction

B. Thermal-expansion methods

C. Thermocouples

D. Electrical-resistance sensors

E. Junction Semi-Conductor sensors

F. Digital Thermometer

G. Pyrometers

A. Introduction

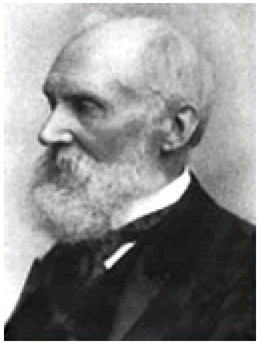
Temperature is a physical property of matter that quantitatively expresses the common notions of hot and cold. **Thermal equilibrium** is a theoretical physical concept, used especially in theoretical texts, that means that all temperatures of interest are unchanging in time and uniform in space

The zero law of thermodynamics: two bodies to be said to have the same temperature, they must be in thermal equilibrium.

Temperature Scale:

- **Thermodynamic Kelvin scale (SI base unit)**
- **Celsius scale**
- **Farenheit scale**
- **Reaumur scale**
- **Rankine scale**
- **International Practical Temperature scale**

Note. The International System of Units = SI



William Thomson

(Lord Kelvin, 1824-1907)

Daniel Fahrenheit (1686-1736)

Anders Celsius

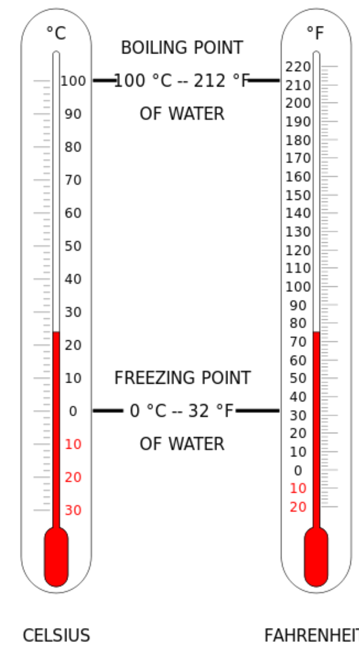
(1701-1744)

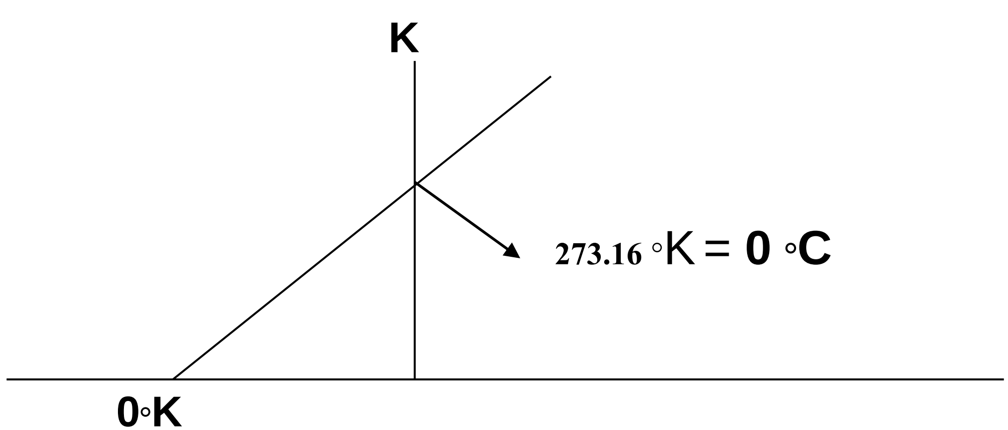
Rene Antoine Ferchault

de Reaumur (1683-1757).

A. Introduction

- 0°C : Water's freezing point
- 100 °C : Water's boiling point
- 0°K : Absolute zero temperature: the energy of its ground state. Absolute zero, the lowest temperature possible, is defined as being exactly 0 K and −273.15 ◦C
- 273.16°K : Water's triple point= 0.01 °C

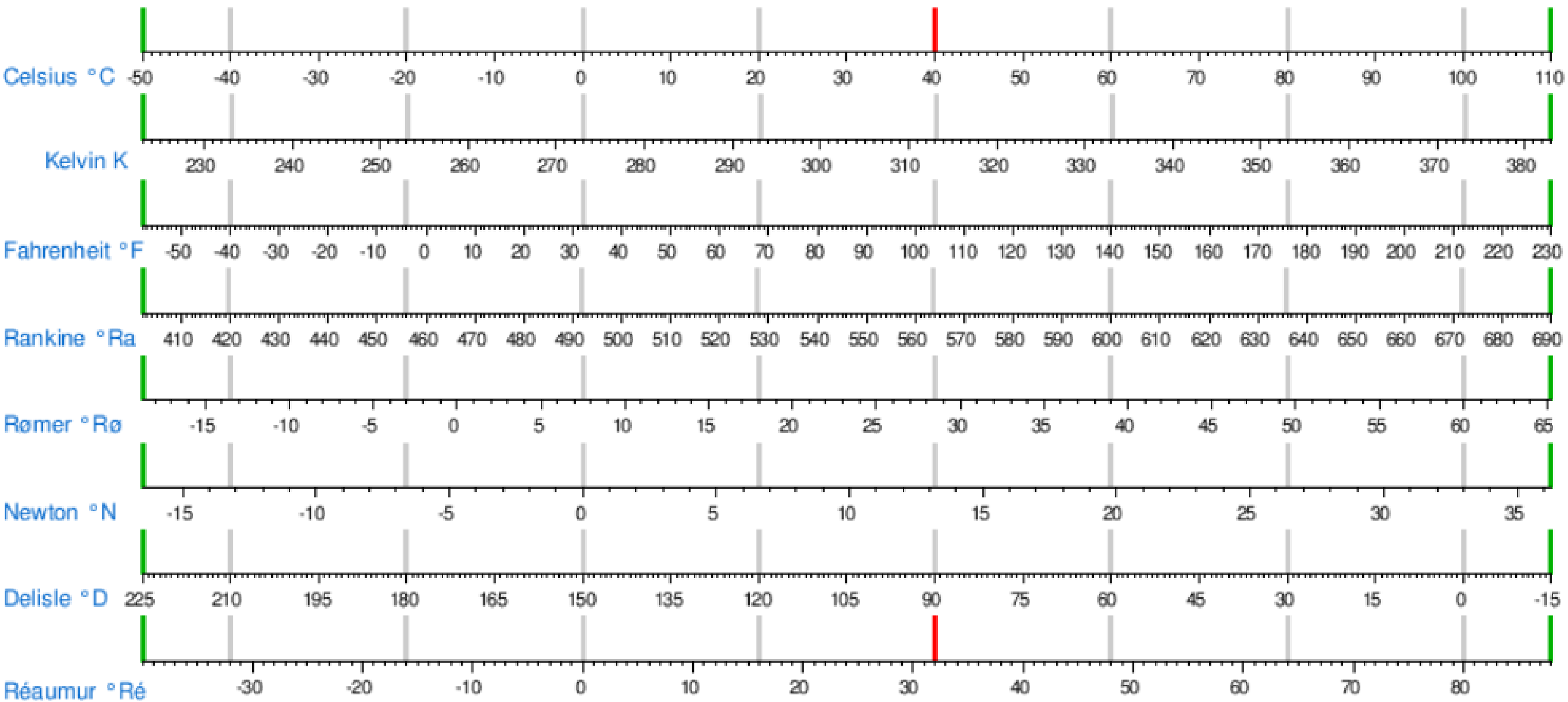




The single combination of pressure and temperature at which water, ice, and water vapour can coexist in a stable equilibrium occurs at exactly 273.16 K (0.01 ◦C) At that point, it is possible to change all of the substance to ice, water, or vapor by making arbitrarily small changes in pressure

and temperature.

Conversion table between the different temperature units



40 °C = 313.15 K = 104 °F = 563.67 °Ra = 28.5 °Rø = 13.2 °N = 90 °D = 32 °Ré

A. Introduction: Principle of temperature measurement

- **Thermal expansion techniques**
  - **Bimetallic**
  - **Liquid-in-glass**
  - **Filled Thermal**
- **Electrical Techniques**
  - **Thermocouples**
  - **Electrical-resistance sensors**
  - **Junction Semi-conductor sensors**
- **Optical and Radiation techniques**
  - **pyrometer**
- **Chemical techniques**
  - **Crayon**
  - **Lacker**

*Contact

*Non-Contact

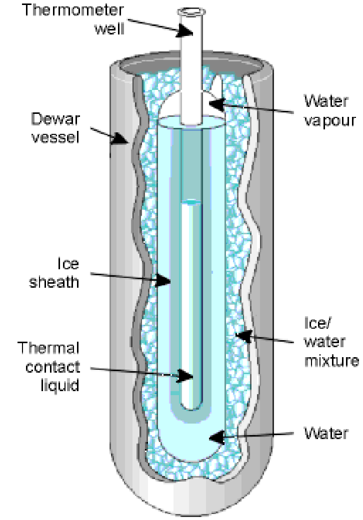
A. Introduction: Standard and Calibration

- International measurement system set up independent standards for only 4 quantities: length, time, mass, and temperature. Standard for all other quantities are basically derived from these.

- In 1927, the International Practical Temperature Scale (IPTS) was defined (revision in 1948, 1954, 1960, 1968, and 1990)

- IPTS was set up to conform as closely as practical with the thermodynamic scale. These primary fixed-point are listed as follows:
  - the triple point of water (0.01 C)
  - the boiling point of liquid oxygen (-182.962 C)
  - the boiling point of water (100 C)
  - the freezing point of zinc (419.58 C)
  - the freezing point of silver (961.93 C)
  - the freezing point of gold (1064.43 C)

A. Introduction: Standard and Calibration



Temperature fixed-point

- **Various secondary point also established:**
  - **A platinum resistance thermometer (-259.34 – 630.74 C)**
  - **A platinum-10% rhodium and platinum thermocouple (630.74-1064.43 C)**

- **International Temperature Scale of 1990 (ITS-90)**

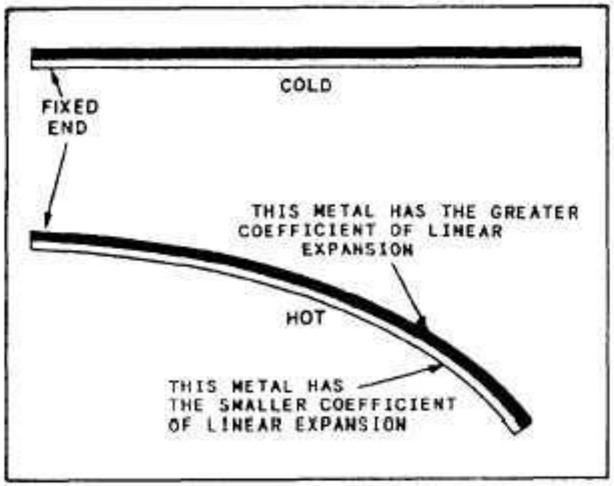
National Institute of Standards and Technology

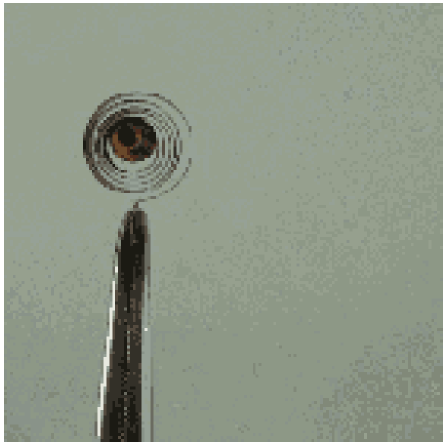
NIST ITS-90 Thermocouple Database

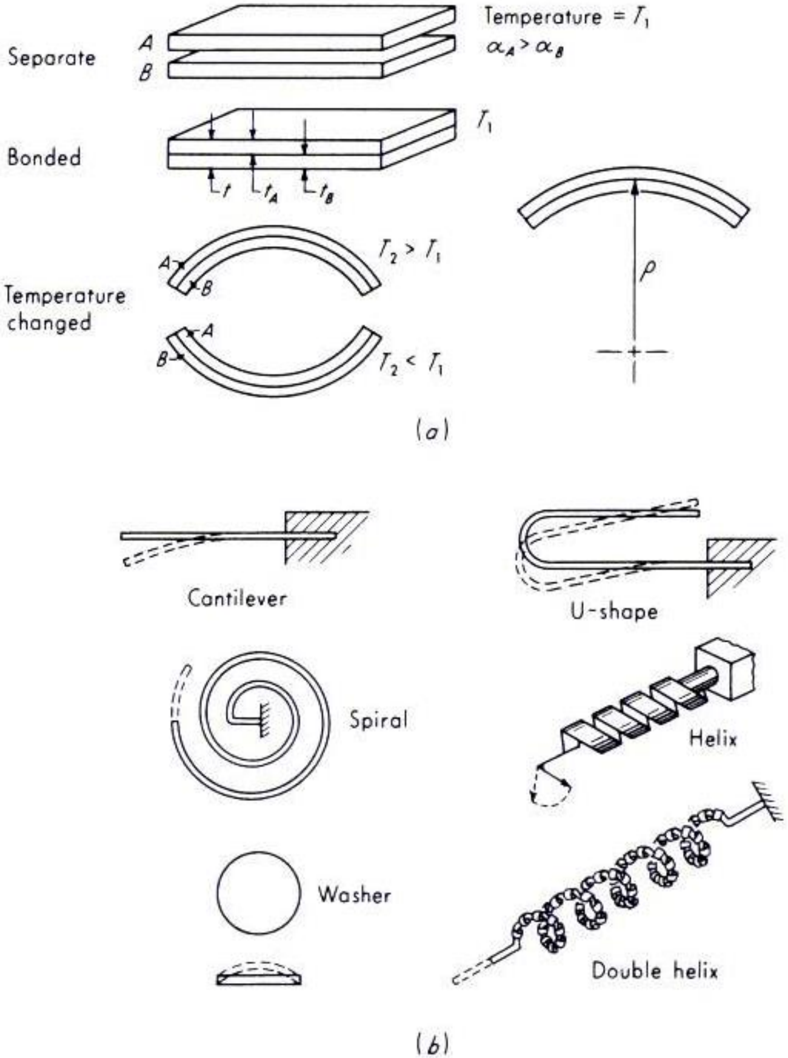
Temperature Calibrator

B. Thermal-expansion methods

B1. Bimetallic Thermometers



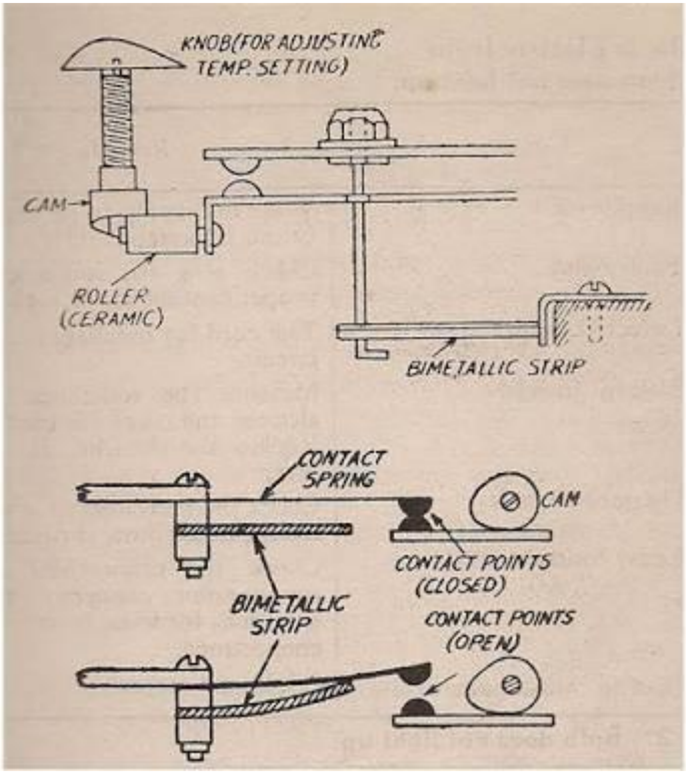




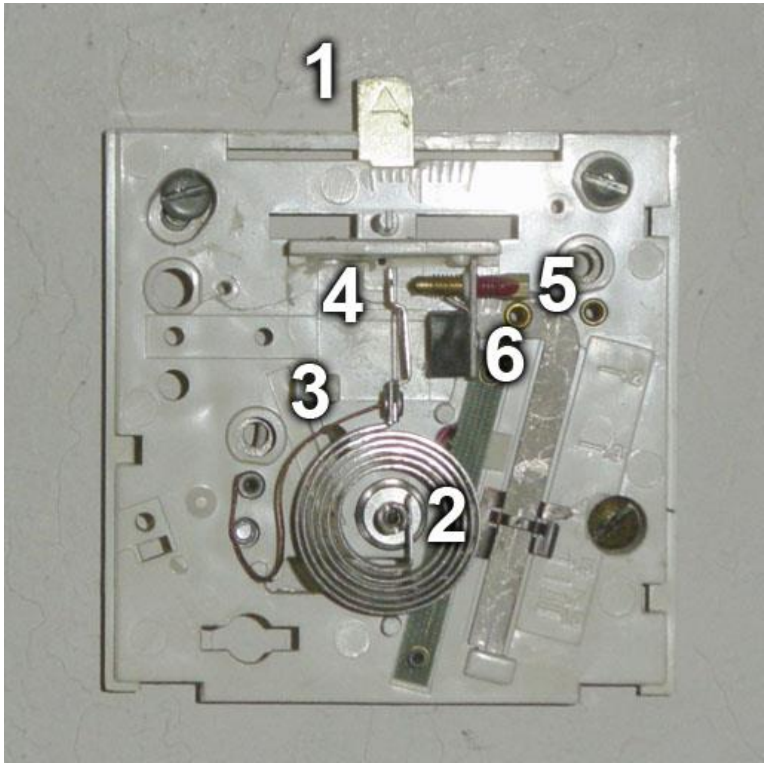
Reference: animation pic https://en.wikipedia.org/wiki/Bimetallic_strip

B. Thermal-expansion methods

B1. Bimetallic Thermometers: Applications



Household iron



Thermostat

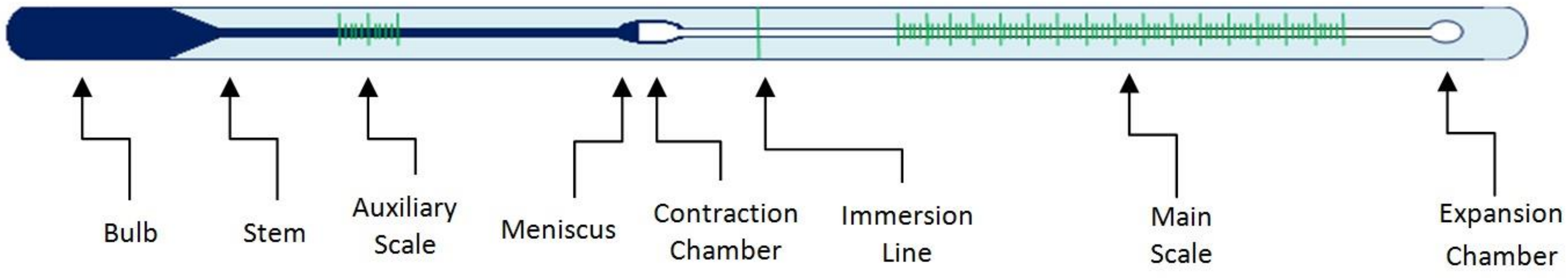
B. Thermometers

B2. Liquid-in-glass Thermometers

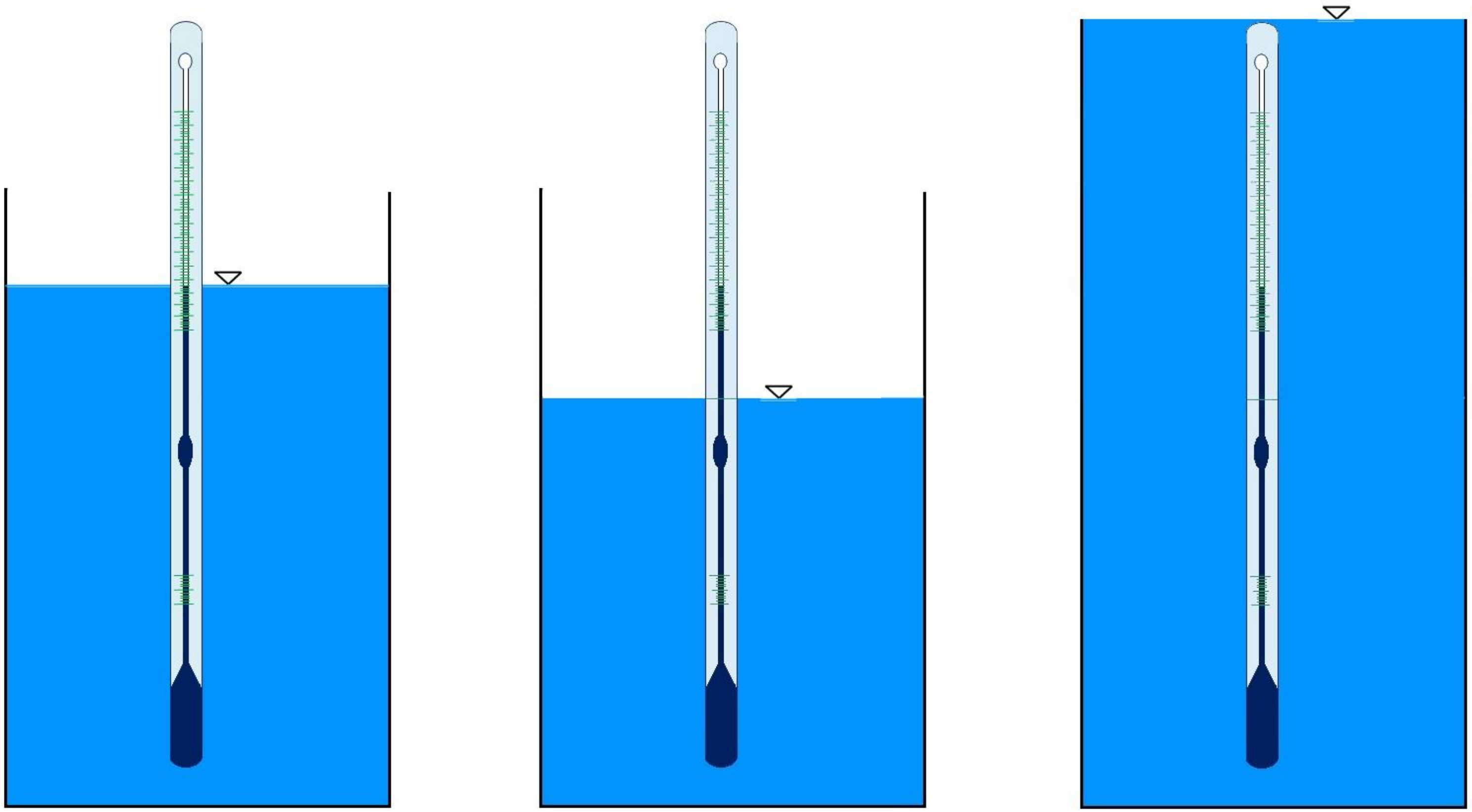
A LiG thermometer is a glass capillary tube with a liquid-filled bulb at one end. As the temperature of the liquid in the reservoir increases, it expands and rises into the capillary tube. The level of the liquid in the column corresponds to a specific temperature, which is marked on the outside of the glass. The liquid that is contained within the thermometer may be one of many different substances, but the most common are mercury, toluene (or a similar organic substance), and low-hazard biodegradable liquids.

- Component

Bulb, Stem, Scale, Contraction Chamber, Expansion Chamber, Immersion Line



B2. Liquid-in-glass Thermometers



Total Immersion Thermometer
Immersed to top of mercury column

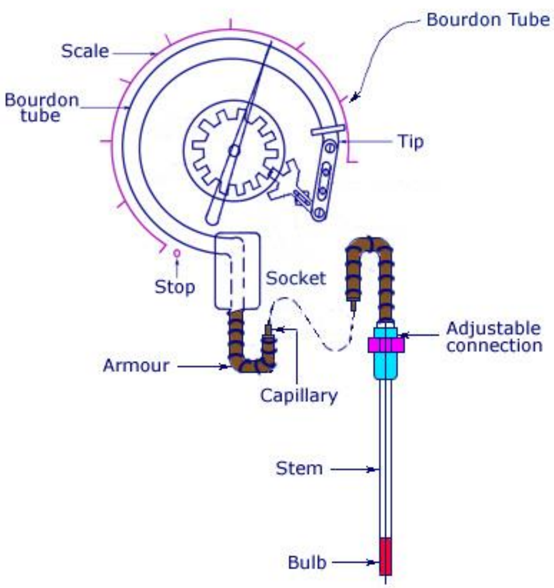
Partial Immersion Thermometer
Immersed to a specific depth

Complete Immersion Thermometer
Entire thermometer immersed

B. Thermal-expansion methods

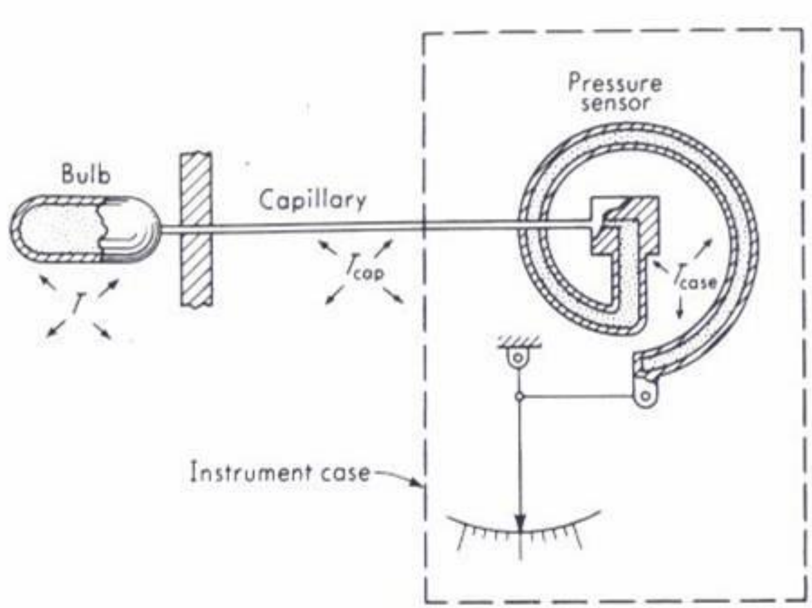
B3. Filled Thermal Thermometers

Filled system temperature measurement systems have been mostly replaced in new facilities with electronic measurements based on thermocouples or RTD's. A liquid will expand or contract in proportion to its temperature and in accordance to the liquid's coefficient of thermal/volumetric expansion. An enclosed liquid will create a definite vapor pressure in proportion to its temperature if the liquid only partially occupies the enclosed space. The pressure of a gas is directly proportional to its temperature in accordance with the basic principle of the universal/perfect gas law: $PV = nRT$ where P = absolute pressure, V = volume, T = absolute temperature, R = universal gas constant and n = number of gas particles (moles).



Filled System Temperature Measurement

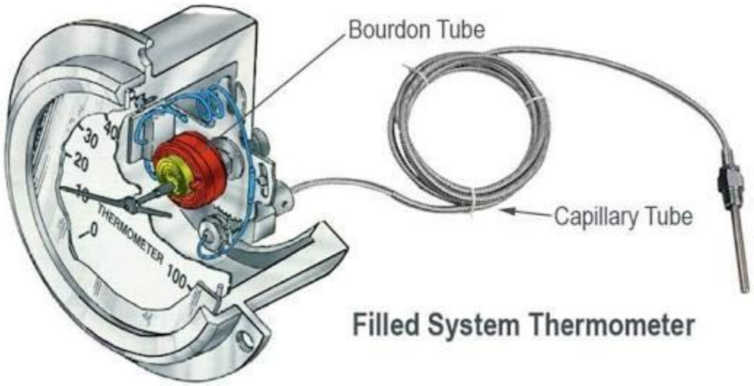
www.InstrumentationToday.com

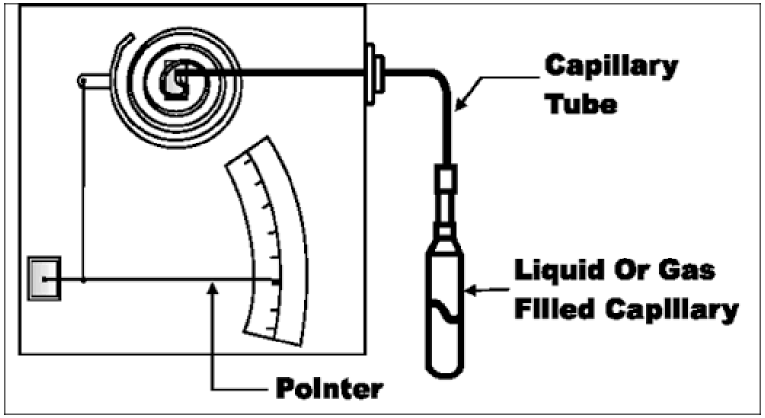


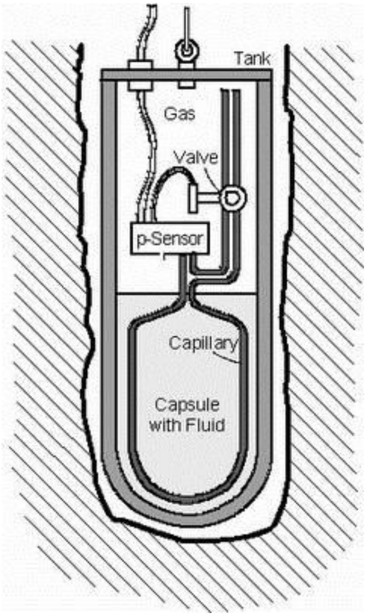
1. **Sensing Bulb**
2. **Capillary Tube**
3. **Pressure Sensing**
4. **Indicator**

B. Thermal-expansion methods

B3. Filled Thermal Thermometers



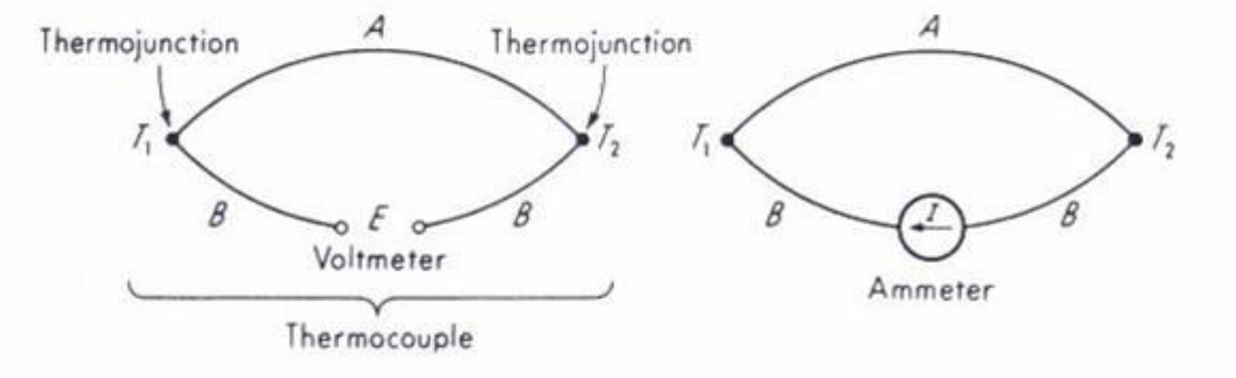




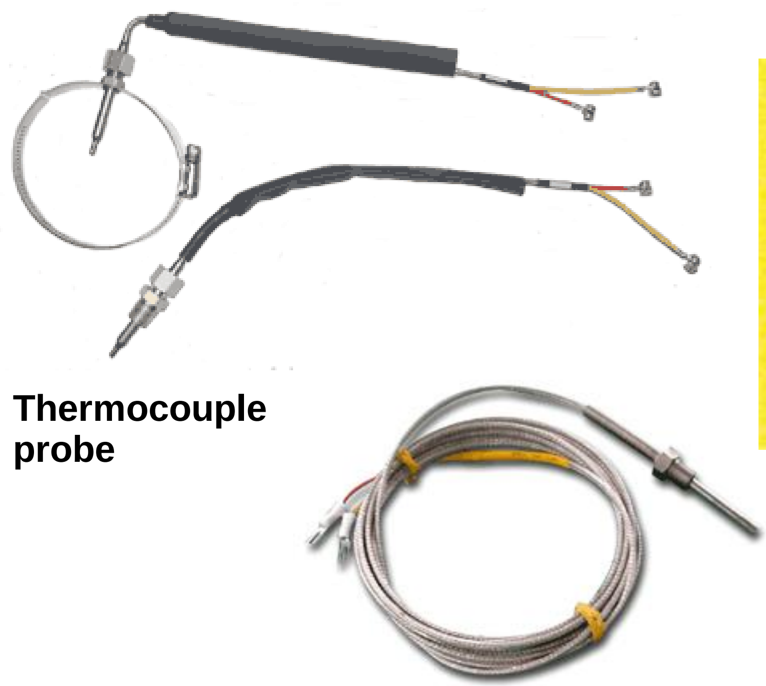
Alternatively, electronic pressure sensors can be used.

C. Thermocouples

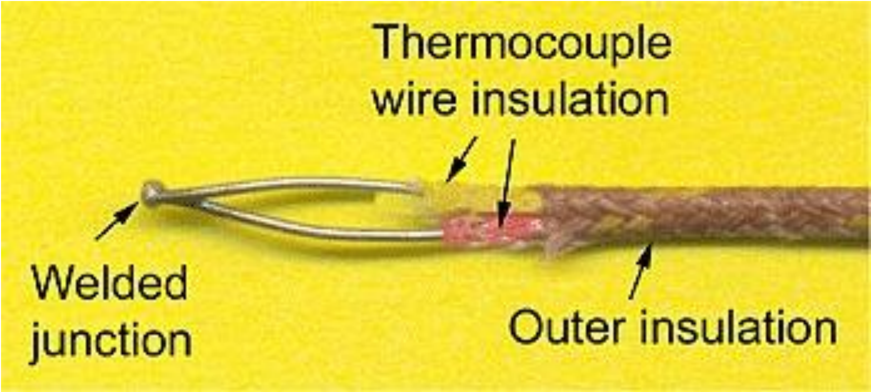
Thermocouple protection head probe



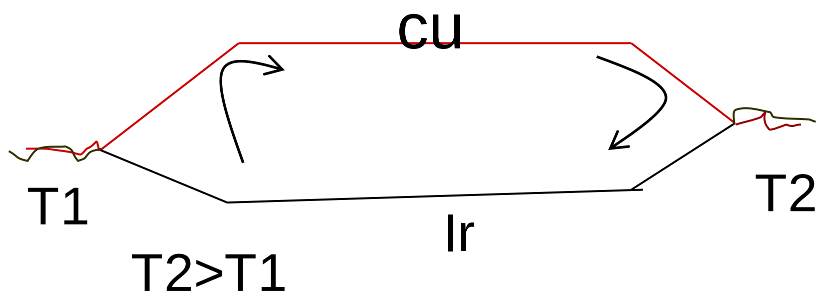
Basic thermocouple



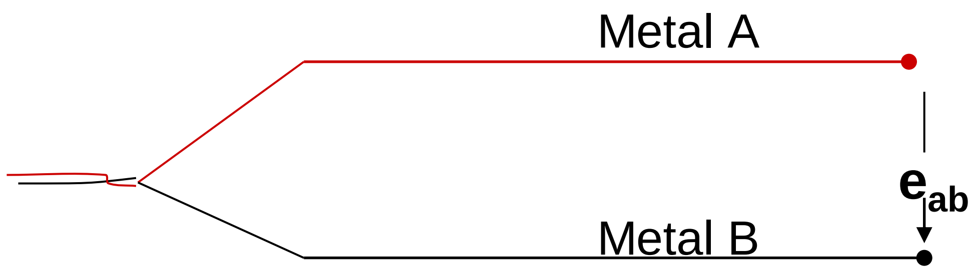
Thermocouple probe



- **Seebeck Effect: bonding wires of two dissimilar metals together to form a closed circuit caused an electrical current to flow in the circuit whenever a difference in temperature was imposed between the end junction.**



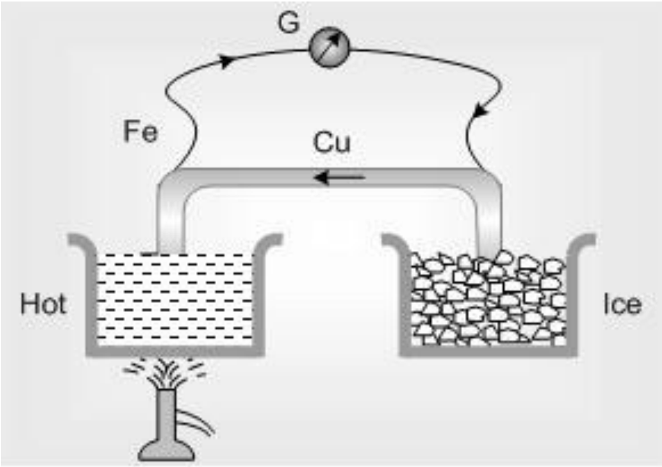
The generated current is depended on the temperature difference of both ends.



e_{ab} = Seebeck Voltage

$e_{ab} = \alpha\Delta T$

where α is Seebeck coefficient



Seebeck Series: The magnitude and direction of thermo emf in a thermocouple depends not only on the temperature difference between the hot and cold junctions but also on the nature of metals constituting the **thermocouple.**

(i) Seebeck arranged different metals in the decreasing order of their electron density. Few metals forming the series are as below.

Sb, Fe, Cd, Zn, Ag, Au, Cr, Sn, Pb, Hg, Mn, Cu, Pt, Co, Ni, Bi

(ii) Thermo electric emf is directly proportional to the distance between the two metals in series. Farther the metals in the series forming the **thermocouple** greater is the thermo emf. Thus maximum thermo emf is obtained for **Sb-Bi** thermo couple

Peltier Effect: **It is reverse of Seeback effect. When the electric current flows in the same direction as the seebeck current, heat is absorbed at the hotter junction and liberated at the colder junction. (fundamental basis for thermoelectric cooling and heating).**

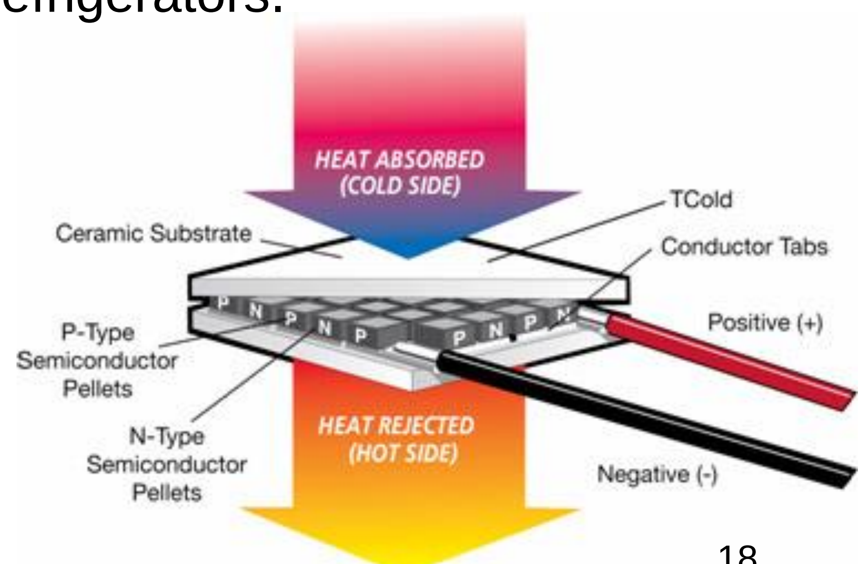
Example **Ir – Cu Junction**

$$Q = ¶ I \Delta T$$

Q = Heat , ¶ = Peltier Coefficient

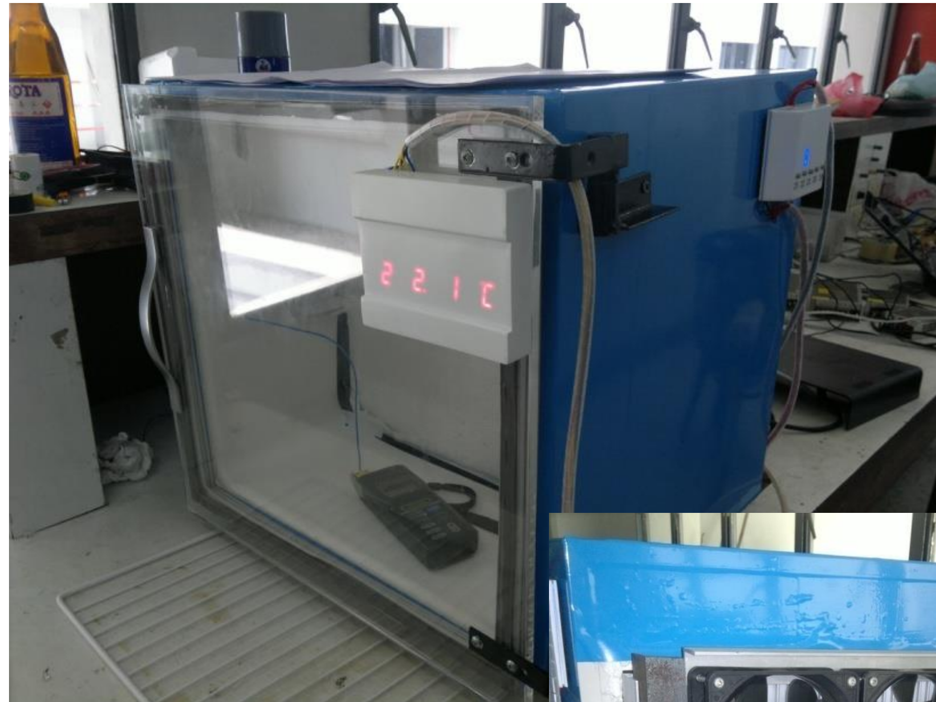
I = current , ΔT = temperature difference

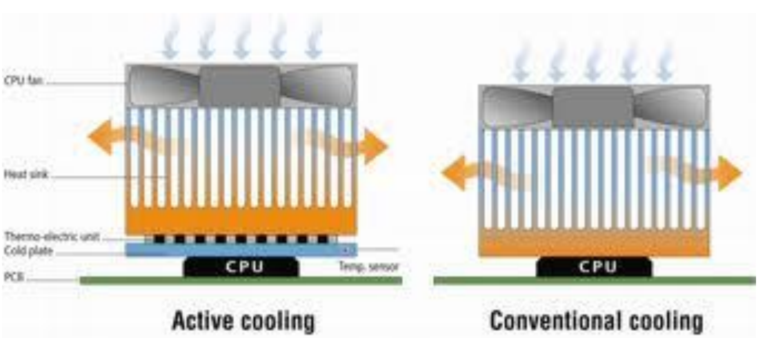
Thermoelectric heat pumps exploit this phenomenon, as do thermoelectric cooling devices found in refrigerators.



Peltier element (1 V, 1 A) cooling one side, heating the other one.

C. Thermocouples: Principle

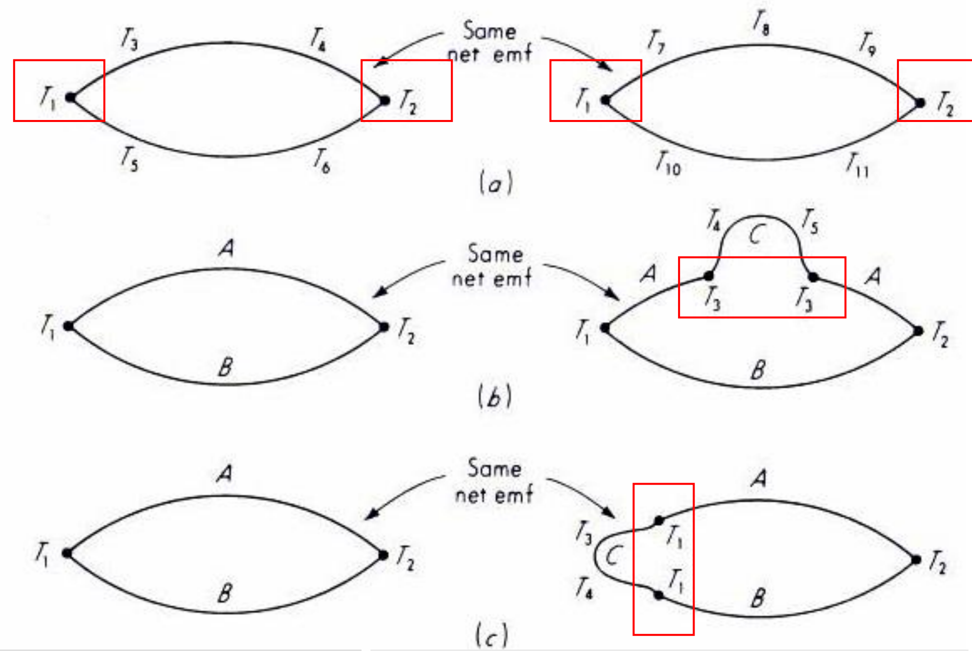


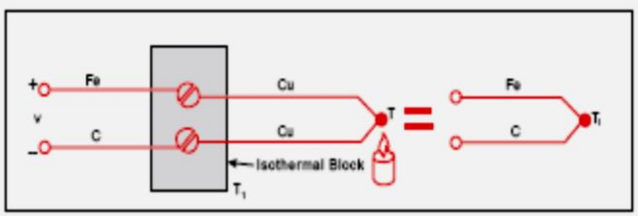


C. Thermocouples: Practical rules

- **Law of the homogeneous circuit:**
A thermocouple current cannot be established in circuit of a single homogeneous material.

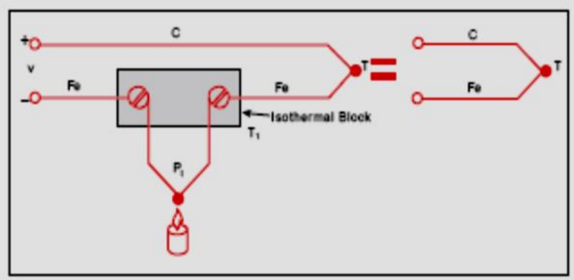
- **Law of Intermediate Material:**
The algebraic sum of the thermo-electromotive forces in a circuit composed of any number of dissimilar materials is zero if all of the circuit is at uniform temperature. This means that a third homogeneous material always can be added to a circuit with no effect on the net EMF of the circuit as long as its extremities are at the same temperature.





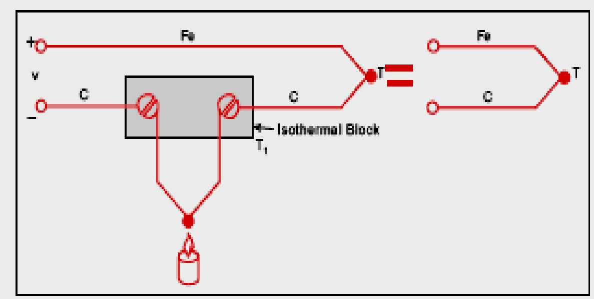
THE LAW OF INTERMEDIATE METALS

Inserting the copper lead between the iron and constantan leads will not change the output voltage V, regardless of the temperature of the copper lead. The voltage V is that of an Fe-C thermocouple at temperature T_1.



THE LAW OF INSERTED METALS

The voltage V will be that of an Fe-C thermocouple at temperature T, provided both ends of the platinum wire are at the same temperature. The two thermocouples created by the platinum wire (FePt and Pt -Fe) act in opposition.

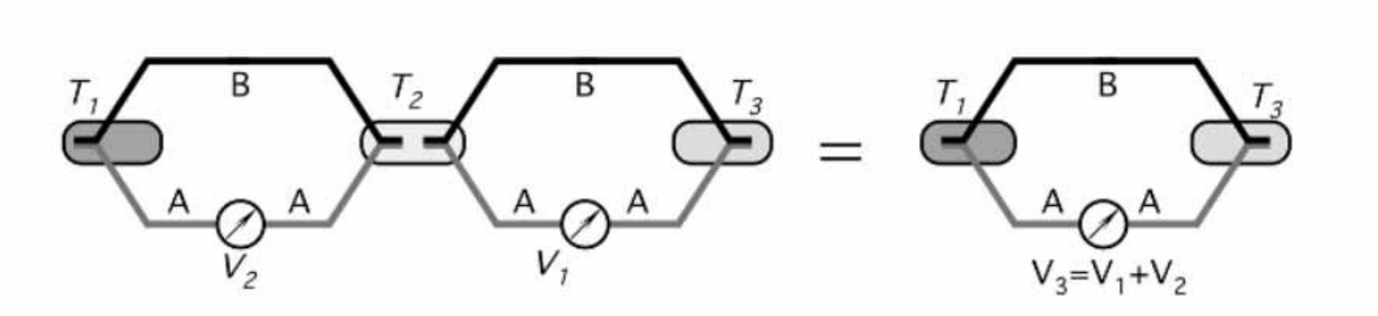


THE LAW OF INTERIOR TEMPERATURES

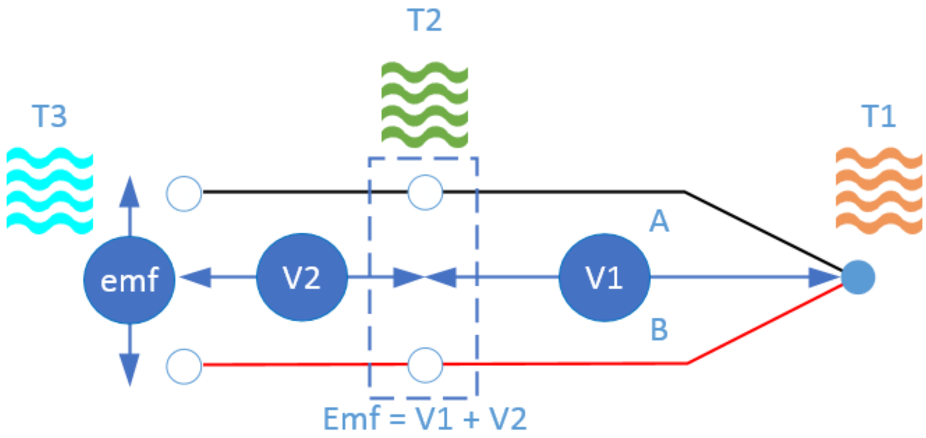
The output voltage V will be that of an Fe-C couple at Temperature T, regardless of the external heat source applied to either measurement lead.

C. Thermocouples: Practical rules

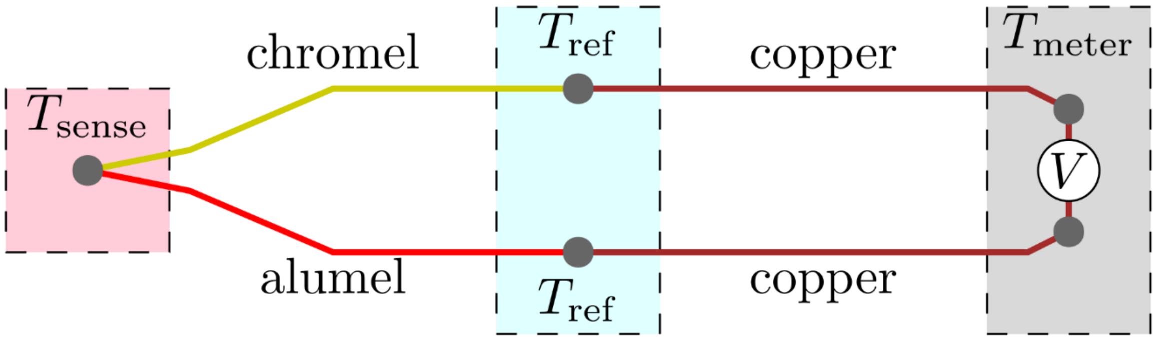
• **Law of Intermediate Temperature:** **Algebraic summation of EMF can be determined when the junctions are at different temperatures (see in figure):**



The law allows us to calibrate a thermocouple at one temperature interval and then to use it at another interval. It also provides that extension wires of the same combination may be inserted into the loop without affecting the accuracy.



C. Thermocouples: Equation



$$V = E(T_{sense}) - E(T_{ref})$$

$$E(T_{sense}) = V + E(T_{ref})$$

Note. E = Electromotive force, abbreviated **emf** (measured in volts) is the electrical intensity or "pressure" developed by a source of electrical energy such as a battery or generator.[2]

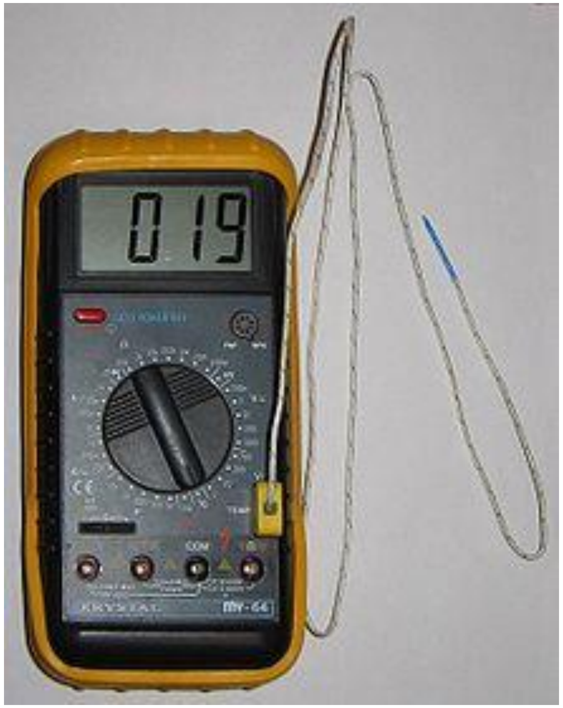
Reference: https://en.wikipedia.org/wiki/Thermocouple

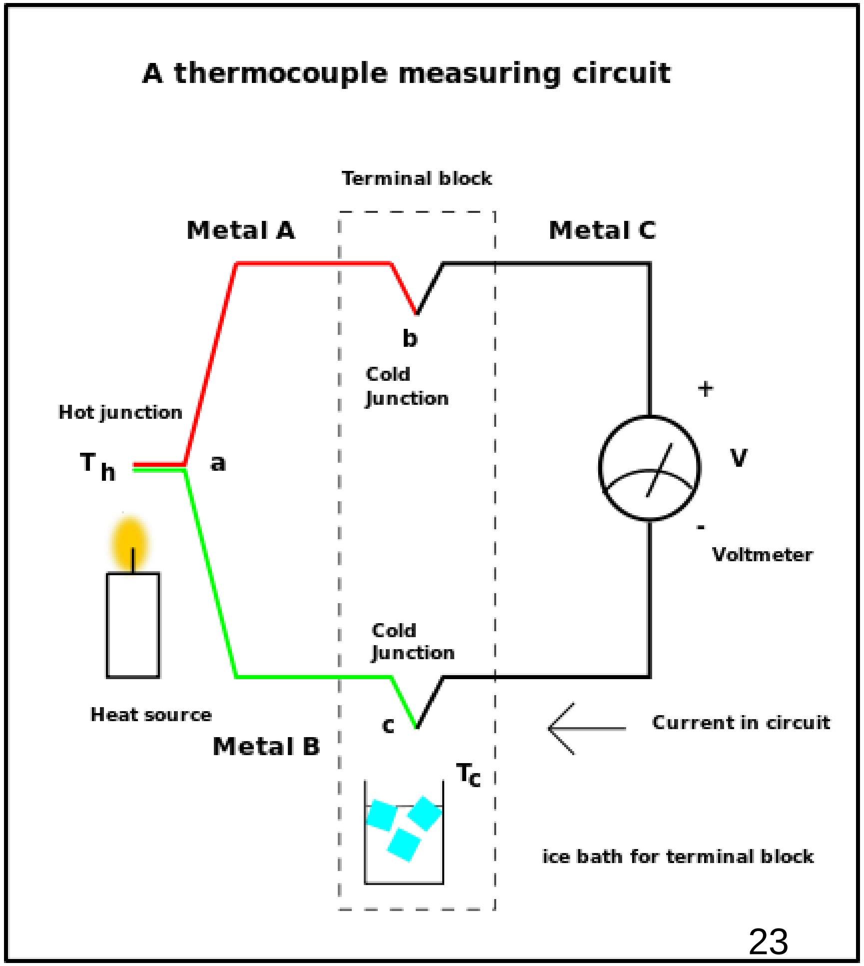
C. Thermocouples: Reference Junction

The end result is a measurement of the difference in temperature between the thermocouple junction and the reference junction.

Reference or Cold Junction Control

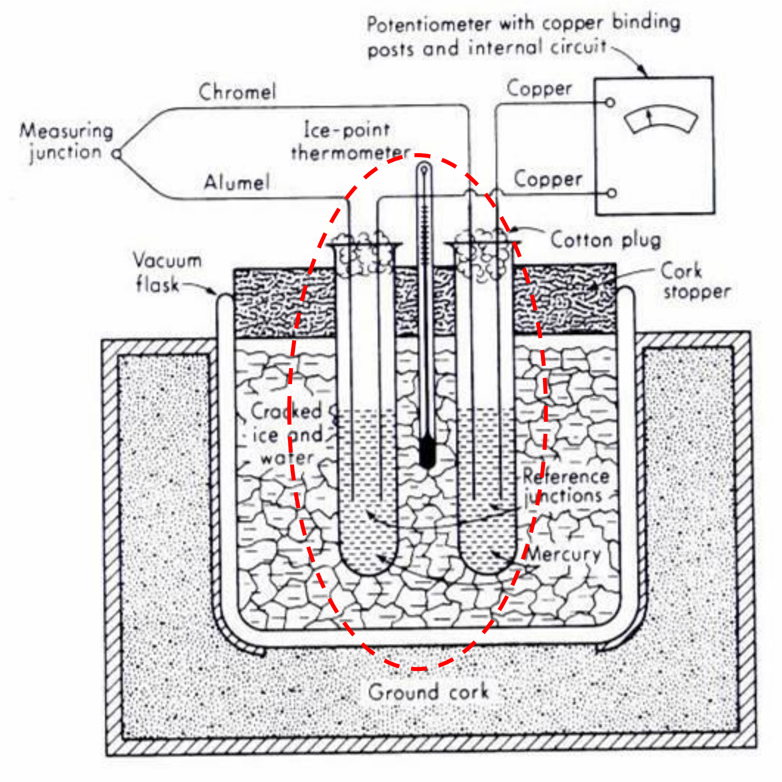
- Fixed Reference Temperature
- Electronic Reference Compensate
- Mechanical Reference Compensate





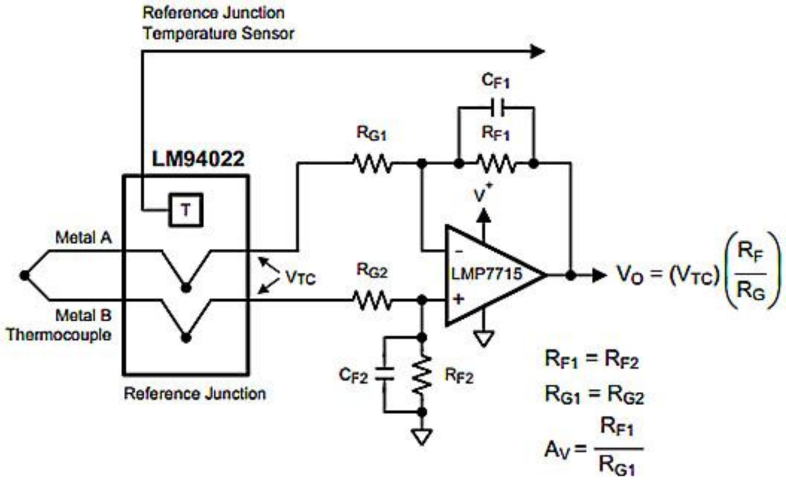
C. Thermocouples: Fixed Reference Temperature

1. Fixed Reference Junction Temperature with ice or fridge or with oven with temperature control at 50 ^{O}C or isothermal block



2. Electrical Reference Compensate

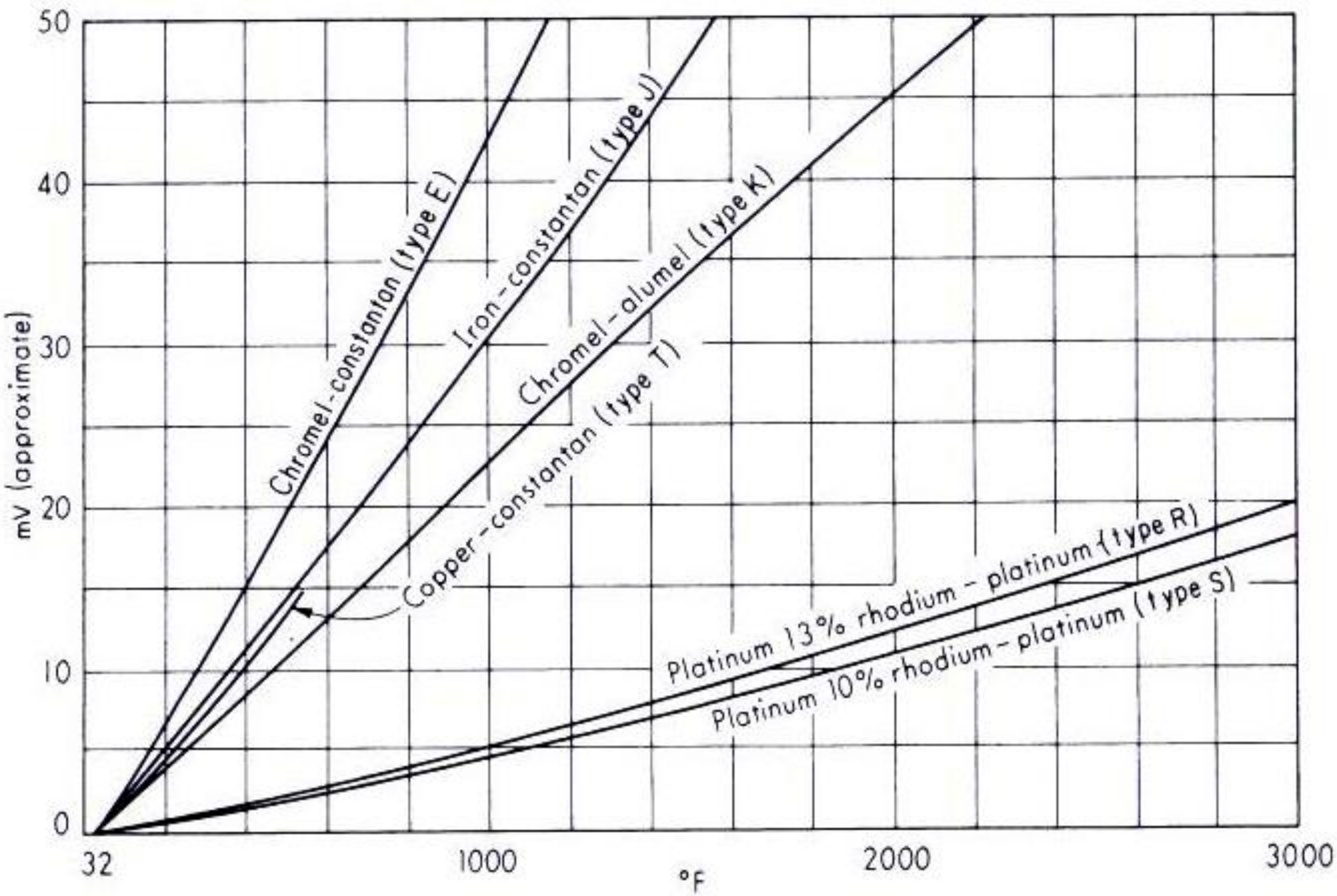
This practical instruments use electronic methods of cold-junction compensation to adjust for varying temperature at the instrument terminals. Electronic instruments can also compensate for the varying characteristics of the thermocouple, and so improve the precision and accuracy of measurements. RTD or Thermister is used in wheatstone bridge to measure the reference junction temperature and compensate the result voltage.



3. Mechanical Reference Compensate

This technique applies to the instrument with moving coil display. The bimetallic component measured the reference junction temperature and automatically adjust the display mechanism.

C. Thermocouples: Principle



Thermocouple temperature/voltage curves.

C. Thermocouples: Principle

Comparison between standard thermocouples

Type	Material	temp range (C)	E (mV)	Oxidizing*	Reducing*	Vacuum*
J	Iron – Constantan[1]	-210 - 760	-8.096 - 42.922	y	y	y
K	Cromel [2]- Alumel [3]	-270 - 1372	-6.458 - 54.875	y	n	n
T	Copper - Constantan	-270 - 400	-6.258 - 20.869	y	y	y
E	Chromel - Constantan	-270 - 1000	-9.835 - 76.358	y	n	n
R	Platinum 13% Rhodium - Platinum	-50 - 1768	-2.26 - 21.108	y	n	n
S	Platinum 10% Rhodium - Platinum	-50 - 1768	-0.236 - 18.698	y	n	n

* No protection tube

[1] Copper(60%)-Nickel(40%)

[2] Nickel(90%)-Chromium(10%)

[3] Nickel(95%)-Manganese(2%)-Aluminum(2%)-Silicon(1%)

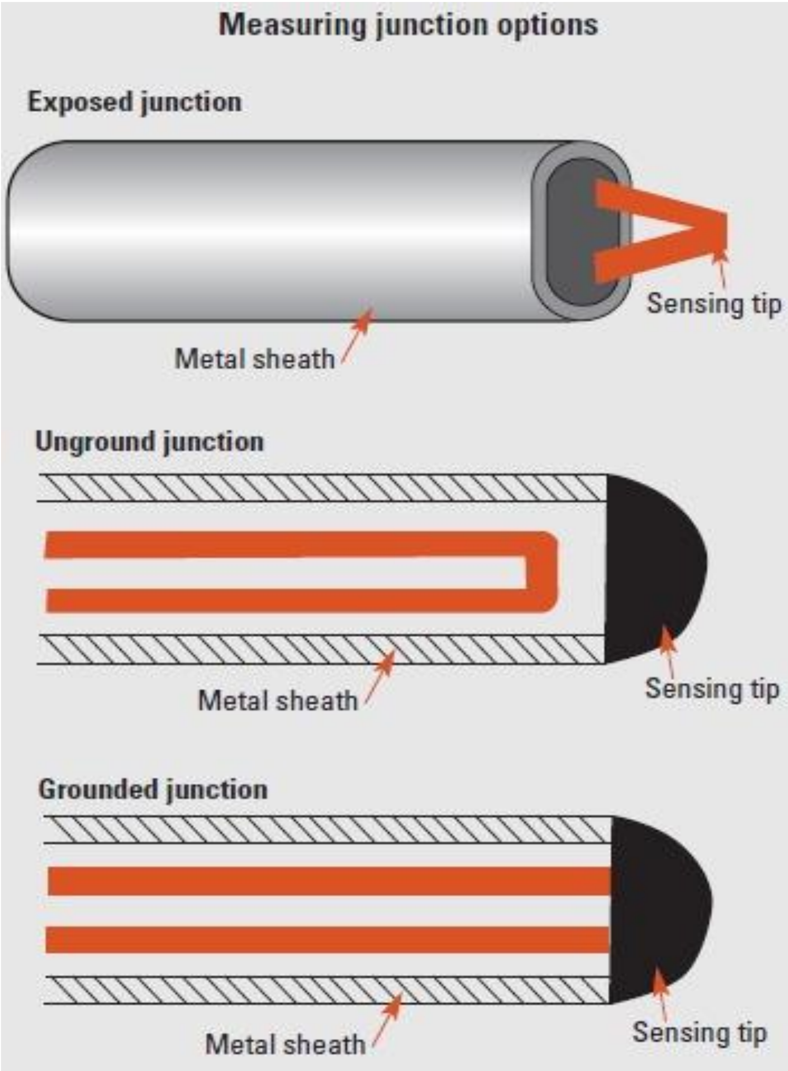
C. Thermocouples: Extension Wire

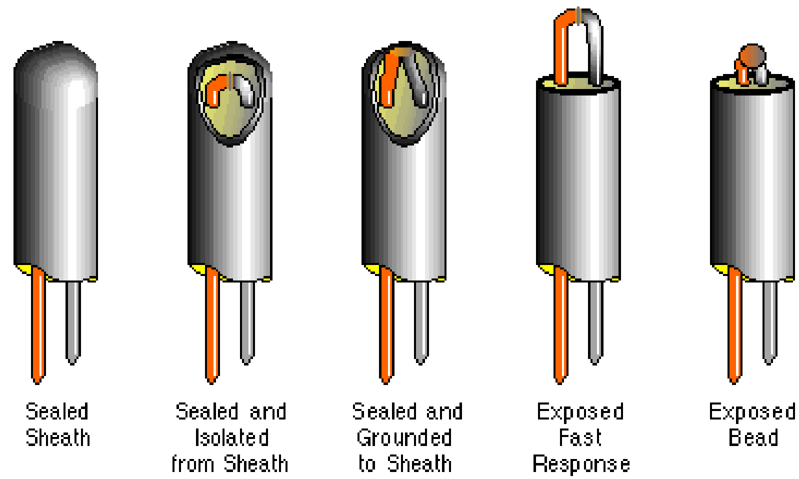
1. Extension wires made of the same metals as a higher-grade thermocouple are used to connect it to a measuring instrument some distance away without introducing additional junctions between dissimilar materials which would generate unwanted voltages; the connections to the extension wires, being of like metals, do not generate a voltage. **Same metals as thermocouple**

2. In the case of platinum thermocouples, extension wire is a copper alloy, since it would be prohibitively expensive to use platinum for extension wires. The extension wire is specified to have a very similar thermal coefficient of EMF to the thermocouple, but only over a narrow range of temperatures; this reduces the cost significantly.

Note. Thermocouple wire may be used as extension wire, but extension grade wire may not be used in the sensing point (or probe part) of the thermocouple.

C. Thermocouples: Tips style





Thermocouple Sheath Options

ISE, Inc.

ITS-90 Table for Type J Thermocouple (Ref Junction 0°C) http://iseinc.com

J

°C	0	1	2	3	4	5	6	7	8	9	10
	Thermoelectric Voltage in mV										
0	0.000	0.050	0.101	0.151	0.202	0.253	0.303	0.354	0.405	0.456	0.507
10	0.507	0.558	0.609	0.660	0.711	0.762	0.814	0.865	0.916	0.968	1.019
20	1.019	1.071	1.122	1.174	1.226	1.277	1.329	1.381	1.433	1.485	1.537
30	1.537	1.589	1.641	1.693	1.745	1.797	1.849	1.902	1.954	2.006	2.059
40	2.059	2.111	2.164	2.216	2.269	2.322	2.374	2.427	2.480	2.532	2.585
50	2.585	2.638	2.691	2.744	2.797	2.850	2.903	2.956	3.009	3.062	3.116
60	3.116	3.169	3.222	3.275	3.329	3.382	3.436	3.489	3.543	3.596	3.650
70	3.650	3.703	3.757	3.810	3.864	3.918	3.971	4.025	4.079	4.133	4.187
80	4.187	4.240	4.294	4.348	4.402	4.456	4.510	4.564	4.618	4.672	4.726
90	4.726	4.781	4.835	4.889	4.943	4.997	5.052	5.106	5.160	5.215	5.269
100	5.269	5.323	5.378	5.432	5.487	5.541	5.595	5.650	5.705	5.759	5.814
110	5.814	5.868	5.923	5.977	6.032	6.087	6.141	6.196	6.251	6.306	6.360
120	6.360	6.415	6.470	6.525	6.579	6.634	6.689	6.744	6.799	6.854	6.909
130	6.909	6.964	7.019	7.074	7.129	7.184	7.239	7.294	7.349	7.404	7.459
140	7.459	7.514	7.569	7.624	7.679	7.734	7.789	7.844	7.900	7.955	8.010
150	8.010	8.065	8.120	8.175	8.231	8.286	8.341	8.396	8.452	8.507	8.562
160	8.562	8.618	8.673	8.728	8.783	8.839	8.894	8.949	9.005	9.060	9.115
170	9.115	9.171	9.226	9.282	9.337	9.392	9.448	9.503	9.559	9.614	9.669
180	9.669	9.725	9.780	9.836	9.891	9.947	10.002	10.057	10.113	10.168	10.224
190	10.224	10.279	10.335	10.390	10.446	10.501	10.557	10.612	10.668	10.723	10.779
200	10.779	10.834	10.890	10.945	11.001	11.056	11.112	11.167	11.223	11.278	11.334
210	11.334	11.389	11.445	11.501	11.556	11.612	11.667	11.723	11.778	11.834	11.889
220	11.889	11.945	12.000	12.056	12.111	12.167	12.222	12.278	12.334	12.389	12.445
230	12.445	12.500	12.556	12.611	12.667	12.722	12.778	12.833	12.889	12.944	13.000
240	13.000	13.056	13.111	13.167	13.222	13.278	13.333	13.389	13.444	13.500	13.555
250	13.555	13.611	13.666	13.722	13.777	13.833	13.888	13.944	13.999	14.055	14.110
260	14.110	14.166	14.221	14.277	14.332	14.388	14.443	14.499	14.554	14.609	14.665

K°C

TABLE 9 ***Type K Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

Thermoelectric Voltage in Millivolts

°C	0	1	2	3	4	5	6	7	8	9	10	°C
-270	-6.458											-270
-260	-6.411	-6.444	-6.446	-6.448	-6.450	-6.452	-6.453	-6.455	-6.456	-6.457	-6.458	-260
-250	-6.404	-6.408	-6.413	-6.417	-6.421	-6.425	-6.429	-6.432	-6.435	-6.438	-6.441	-250
-240	-6.344	-6.351	-6.358	-6.364	-6.370	-6.377	-6.382	-6.388	-6.393	-6.399	-6.404	-240
-230	-6.262	-6.271	-6.280	-6.289	-6.297	-6.306	-6.314	-6.322	-6.329	-6.337	-6.344	-230
-220	-6.158	-6.170	-6.181	-6.192	-6.202	-6.213	-6.223	-6.233	-6.243	-6.252	-6.262	-220
-210	-6.035	-6.048	-6.061	-6.074	-6.087	-6.099	-6.111	-6.123	-6.135	-6.147	-6.158	-210
-200	-5.891	-5.907	-5.922	-5.936	-5.951	-5.965	-5.980	-5.994	-6.007	-6.021	-6.035	-200
-190	-5.730	-5.747	-5.763	-5.780	-5.797	-5.813	-5.829	-5.845	-5.861	-5.876	-5.891	-190
-180	-5.550	-5.569	-5.588	-5.606	-5.624	-5.642	-5.660	-5.678	-5.695	-5.713	-5.730	-180
-170	-5.354	-5.374	-5.395	-5.415	-5.435	-5.454	-5.474	-5.493	-5.512	-5.531	-5.550	-170
-160	-5.141	-5.163	-5.185	-5.207	-5.228	-5.250	-5.271	-5.292	-5.313	-5.333	-5.354	-160
-150	-4.913	-4.936	-4.960	-4.983	-5.006	-5.029	-5.052	-5.074	-5.097	-5.119	-5.141	-150
-140	-4.669	-4.694	-4.719	-4.744	-4.768	-4.793	-4.817	-4.841	-4.865	-4.889	-4.913	-140
-130	-4.411	-4.437	-4.463	-4.490	-4.516	-4.542	-4.567	-4.593	-4.618	-4.644	-4.669	-130
-120	-4.138	-4.166	-4.194	-4.221	-4.249	-4.276	-4.303	-4.330	-4.357	-4.384	-4.411	-120
-110	-3.852	-3.882	-3.911	-3.939	-3.968	-3.997	-4.025	-4.054	-4.082	-4.110	-4.138	-110
-100	-3.554	-3.584	-3.614	-3.645	-3.675	-3.705	-3.734	-3.764	-3.794	-3.823	-3.852	-100
-90	-3.243	-3.274	-3.306	-3.337	-3.368	-3.400	-3.431	-3.462	-3.492	-3.523	-3.554	-90
-80	-2.920	-2.953	-2.986	-3.018	-3.050	-3.083	-3.115	-3.147	-3.179	-3.211	-3.243	-80
-70	-2.587	-2.620	-2.654	-2.688	-2.721	-2.755	-2.788	-2.821	-2.854	-2.887	-2.920	-70
-60	-2.243	-2.278	-2.312	-2.347	-2.382	-2.416	-2.450	-2.485	-2.519	-2.553	-2.587	-60
-50	-1.889	-1.925	-1.961	-1.996	-2.032	-2.067	-2.103	-2.138	-2.173	-2.208	-2.243	-50
-40	-1.527	-1.564	-1.600	-1.637	-1.673	-1.709	-1.745	-1.782	-1.818	-1.854	-1.889	-40
-30	-1.156	-1.194	-1.231	-1.268	-1.305	-1.343	-1.380	-1.417	-1.453	-1.490	-1.527	-30
-20	-0.778	-0.816	-0.854	-0.892	-0.930	-0.968	-1.006	-1.043	-1.081	-1.119	-1.156	-20
-10	-0.392	-0.431	-0.470	-0.508	-0.547	-0.586	-0.624	-0.663	-0.701	-0.739	-0.778	-10
0	0.000	-0.039	-0.079	-0.118	-0.157	-0.197	-0.236	-0.275	-0.314	-0.353	-0.392	0
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397	0
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798	10
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.163	1.203	20
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612	30
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023	40
50	2.023	2.064	2.106	2.147	2.188	2.230	2.271	2.312	2.354	2.395	2.436	50
60	2.436	2.478	2.519	2.561	2.602	2.644	2.685	2.727	2.768	2.810	2.851	60
70	2.851	2.893	2.934	2.976	3.017	3.059	3.100	3.142	3.184	3.225	3.267	70
80	3.267	3.308	3.350	3.391	3.433	3.474	3.516	3.557	3.599	3.640	3.682	80
90	3.682	3.723	3.765	3.806	3.848	3.889	3.931	3.972	4.013	4.055	4.096	90
100	4.096	4.138	4.179	4.220	4.262	4.303	4.344	4.385	4.427	4.468	4.509	100
110	4.509	4.550	4.591	4.633	4.674	4.715	4.756	4.797	4.838	4.879	4.920	110
120	4.920	4.961	5.002	5.043	5.084	5.124	5.165	5.206	5.247	5.288	5.328	120
130	5.328	5.369	5.410	5.450	5.491	5.532	5.572	5.613	5.653	5.694	5.735	130
140	5.735	5.775	5.815	5.856	5.896	5.937	5.977	6.017	6.058	6.098	6.138	140
150	6.138	6.179	6.219	6.259	6.299	6.339	6.380	6.420	6.460	6.500	6.540	150

Example: Thermocouple Type K is used to measure the temperature of 400 °C with the reference junction at 25 °C. Calculate the produced emf.

- V(25 °C) = 1 mV (Type K , 0 °C ref.)
- V(400 °C) = 16.40 mV (Type K ,0 °C ref.)

$$V = V_{Tm} - V_{TR}$$

- V(400 °C) = 15.40 mV (Type K , 25 °C ref.)

C. Thermocouples: Calibration

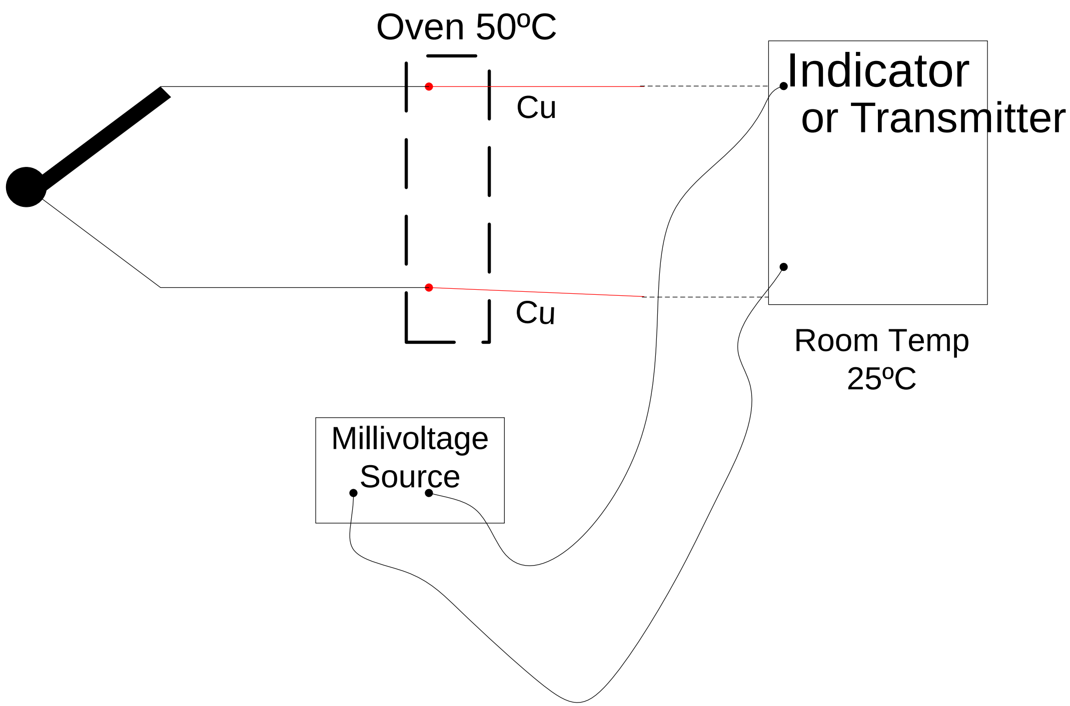
- Transmitter: Zero 4 mA and span 20 mA
- **Using Oven**

  Oven is controlled at 50ºC for a Reference Junction control.

Zero and Span Adjustment at Indicator or Transmitter

Example. The indicator with the range of 0-500ºC used with the thermocouple Type K is calibrated with Millivoltage source.

Zero Adjustment



Consider as measure real 0ºC but instead of using thermocouple, the voltage is generated from a millivoltage source.

Methods

V(0 °C) = 0 mV (Type K , 0 °C ref.)

V(50 °C) = 2.02 mV (Type K ,0 °C ref.)

$$V = V_{Tm} - V_{TR}$$

Therefore, to adjust the zero(0ºC), users must adjust the voltage source to generate voltage = 0.0000 – 2.02 = -2.02 mV

Then , adjust the zero scale of indicator to 0ºC or adjust the transmitter to source 4 mA

Span Adjustment

Consider as measure 500ºC but instead of using thermocouple, the voltage is generated from a millivoltage source.

Methods

V(500 °C)= 20.65 mV (Type K , 0 °C ref.)

V(50 °C) = 2.02 mV (Type K ,0 °C ref.)

Therefore, to adjust the span(500ºC), users must adjust the voltage source to generate voltage = 20.65 – 2.02 = 18.63 mV

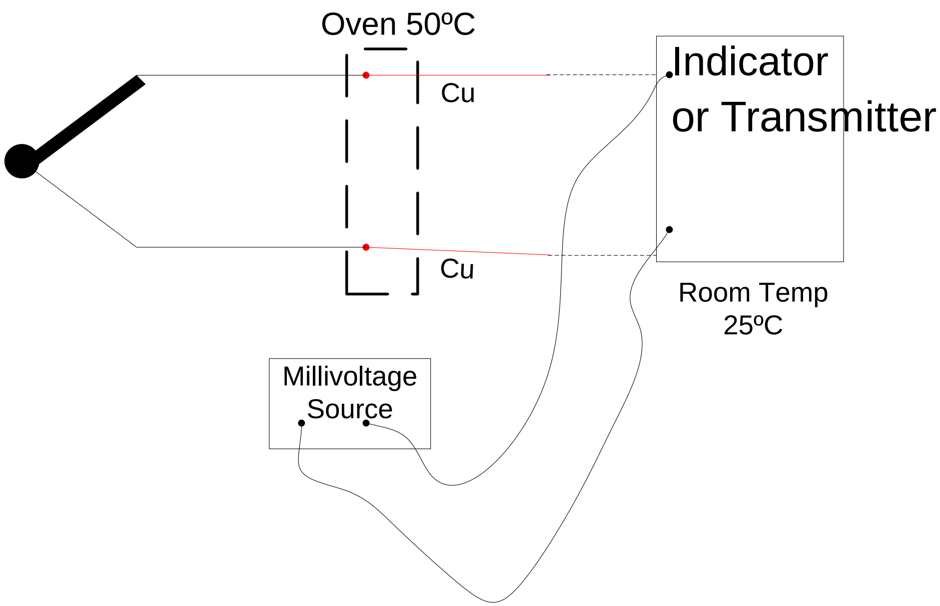
Then , adjust the span scale of indicator to 500ºC or adjust the transmitter to be 20 mA.

In practical, zero and span adjustment must done many times by changing the generating voltage between zero and span until getting the desired values.

vs Smart Transmitter

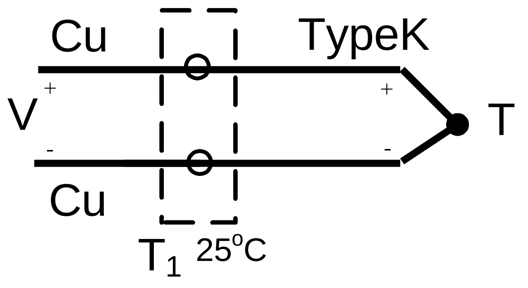
Example (1)

From a given figure, explain the method to calibrate the transmitter with the temperature range of 0 ^{0}C to 150 ^{0}C.



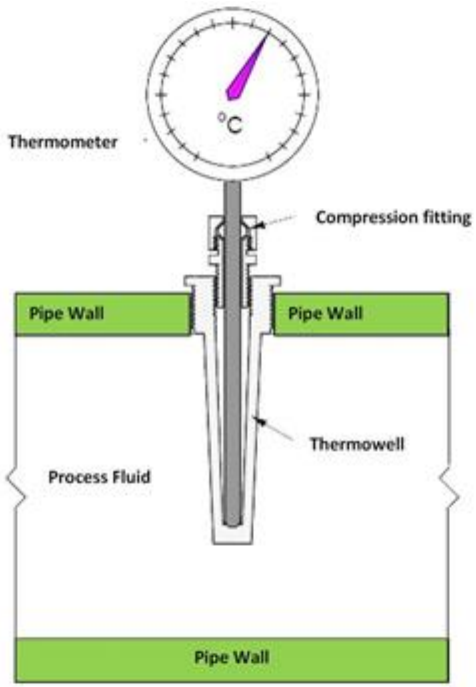
Example (2)

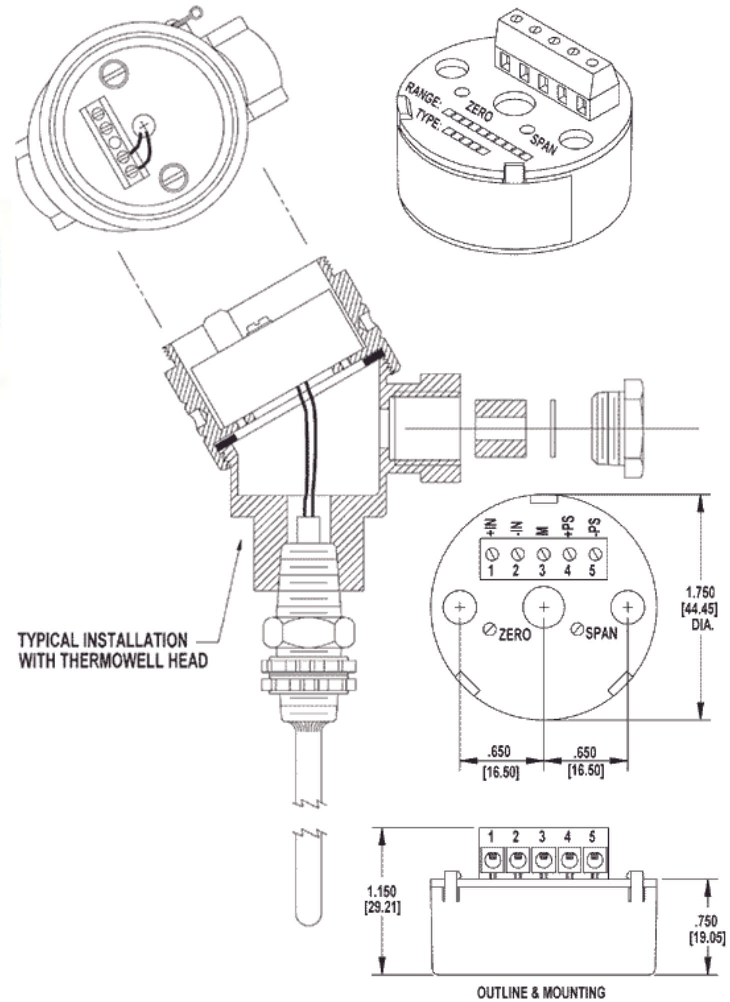
From a given figure, if the measured voltage (V) is between 0 mV and 5 mV, calculate the temperature range of this thermocouple in degree Celsius



C. Thermocouples: Thermowell

For intrusive fitting, protection, easy cleaning. But slow down the response





D. Electrical-resistance sensors

D1. Resistance thermometer (RTD)

Sir Humphrey Dery found the relation between temperature and metal resistance. In 1835, Faraday invented Resistance Thermometer based on thermoresistive principle.

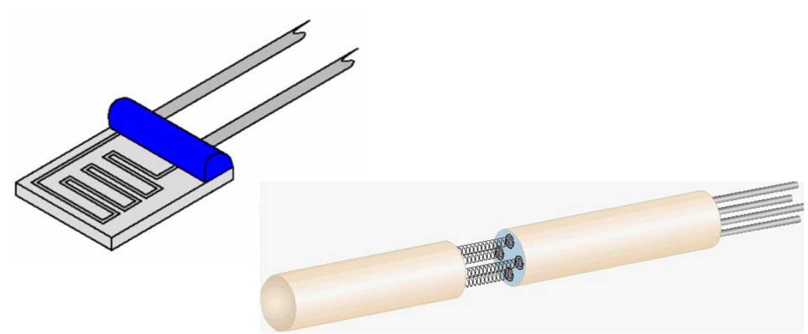
Resistance temperature detectors (**RTD**s), are sensors used to measure temperature by correlating the resistance of the RTD element with temperature.

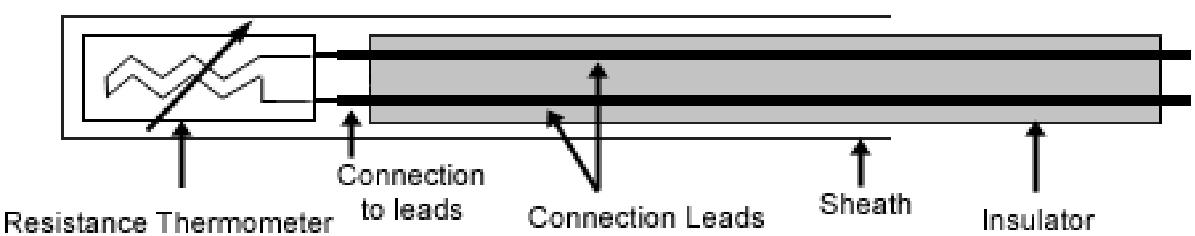
$$R_t = R_0\left(1+\alpha t\right) \Rightarrow R_2 = R_1 + R_0\alpha\left(t_2 - t_1\right)$$

R_0 : the resistance of the sensor at 0°C

R_t : the resistance of the sensor at t°C

α : temperature coefficient of resistance





D. Electrical-resistance sensors

D1. Resistance thermometer (RTD)

$$R_T = R_0(1 + aT + bT^2 + cT^3 + ...)$$

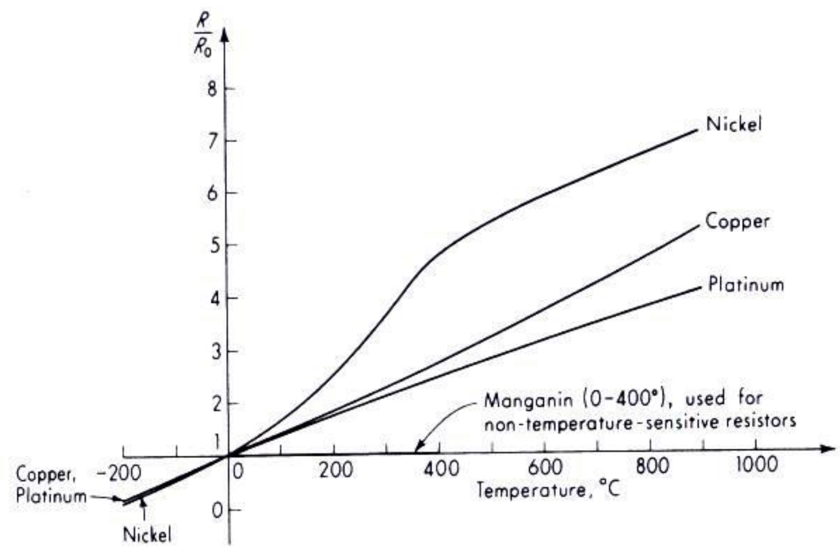
where R_0 = resistance at reference temperature

R_T = resistance at temperature T

a,b,c = temperature coefficients

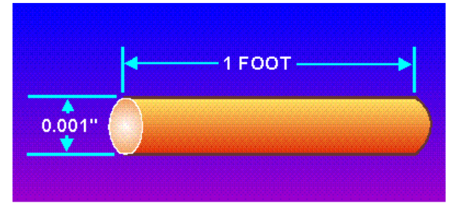
RTD protection head probe

RTD probe



Resistance/temperature curves.

METAL		RESISTIVITY OHM/CMF (cmf = circular mil foot)
Gold	Au	13.00
Silver	Ag	8.8
Copper	Cu	9.26
Platinum	Pt	59.00
Tungsten	w	30.00
Nickel	Ni	36.00



Mil is a **thousandth of an inch** derived unit of length in an inch-based system of units. Equal to 0.001 inches.

Platinum Resistance Thermometer

- Popular type RTD, wide measuring range, the most stable resistance to temperature relationship over the largest temperature range, hazardous environment, temperature coefficient of resistance = 0.00385Ω/ Ω/ºC [Commercial platinum grades] , standard for Eurepean, accurate, range : -100 to 890 ºC (PT-100),
- PT-100 : at 0 ºC =100 Ω
- PT-50 : at 0 ºC =50 Ω

Nickel and Copper Resistance Thermometer

- Nickel RTD: non standard , limited temperature range, very non-linear at temperatures over 572 F (300 ºC) , temperature coefficient of resistance = 0.0066 Ω/ Ω/ºC
- Copper Resistance Thermometer: very linear resistance to temperature relationship, measurement range -200 to 150ºC (limited due to oxidizes), resistance standard 10 Ω and 25 Ω at 0ºC

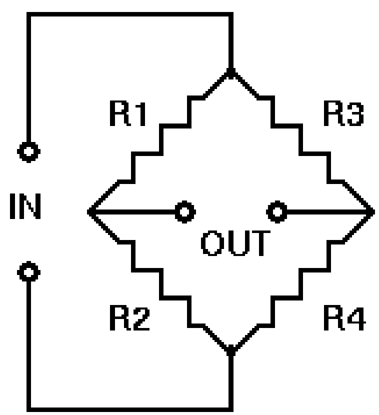
PT100 Resistance Table

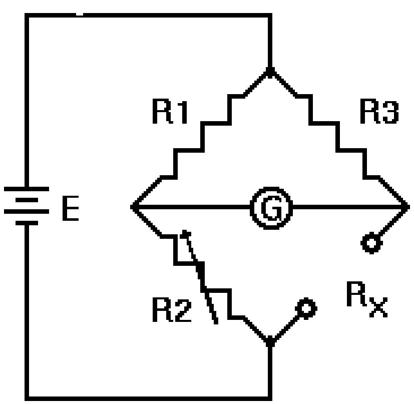
°C	0	1	2	3	4	5	6	7	8	9	°C
-200.00	18.52										-200.00
-190.00	22.83	22.40	21.97	21.54	21.11	20.68	20.25	19.82	19.38	18.95	-190.00
-180.00	27.10	26.67	26.24	25.82	25.39	24.97	24.54	24.11	23.68	23.25	-180.00
-170.00	31.34	30.91	30.49	30.07	29.64	29.22	28.80	28.37	27.95	27.52	-170.00
-160.00	35.54	35.12	34.70	34.28	33.86	33.44	33.02	32.60	32.18	31.76	-160.00
-150.00	39.72	39.31	38.89	38.47	38.05	37.64	37.22	36.80	36.38	35.96	-150.00
-140.00	43.88	43.46	43.05	42.63	42.22	41.80	41.39	40.97	40.56	40.14	-140.00
-130.00	48.00	47.59	47.18	46.77	46.36	45.94	45.53	45.12	44.70	44.29	-130.00
-120.00	52.11	51.70	51.29	50.88	50.47	50.06	49.65	49.24	48.83	48.42	-120.00
-110.00	56.19	55.79	55.38	54.97	54.56	54.15	53.75	53.34	52.93	52.52	-110.00
-100.00	60.26	59.85	59.44	59.04	58.63	58.23	57.82	57.41	57.01	56.60	-100.00
-90.00	64.30	63.90	63.49	63.09	62.68	62.28	61.88	61.47	61.07	60.66	-90.00
-80.00	68.33	67.92	67.52	67.12	66.72	66.31	65.91	65.51	65.11	64.70	-80.00
-70.00	72.33	71.93	71.53	71.13	70.73	70.33	69.93	69.53	69.13	68.73	-70.00
-60.00	76.33	75.93	75.53	75.13	74.73	74.33	73.93	73.53	73.13	72.73	-60.00
-50.00	80.31	79.91	79.51	79.11	78.72	78.32	77.92	77.52	77.12	76.73	-50.00
-40.00	84.27	83.87	83.48	83.08	82.69	82.29	81.89	81.50	81.10	80.70	-40.00
-30.00	88.22	87.83	87.43	87.04	86.64	86.25	85.85	85.46	85.06	84.67	-30.00
-20.00	92.16	91.77	91.37	90.98	90.59	90.19	89.80	89.40	89.01	88.62	-20.00
-10.00	96.09	95.69	95.30	94.91	94.52	94.12	93.73	93.34	92.95	92.55	-10.00
0.00	100.00	99.61	99.22	98.83	98.44	98.04	97.65	97.26	96.87	96.48	0.00
0.00	100.00	100.39	100.78	101.17	101.56	101.95	102.34	102.73	103.12	103.51	0.00
10.00	103.90	104.29	104.68	105.07	105.46	105.85	106.24	106.63	107.02	107.40	10.00
20.00	107.79	108.18	108.57	108.96	109.35	109.73	110.12	110.51	110.90	111.29	20.00
30.00	111.67	112.06	112.45	112.83	113.22	113.61	114.00	114.38	114.77	115.15	30.00
40.00	115.54	115.93	116.31	116.70	117.08	117.47	117.86	118.24	118.63	119.01	40.00
50.00	119.40	119.78	120.17	120.55	120.94	121.32	121.71	122.09	122.47	122.86	50.00
60.00	123.24	123.63	124.01	124.39	124.78	125.16	125.54	125.93	126.31	126.69	60.00
70.00	127.08	127.46	127.84	128.22	128.61	128.99	129.37	129.75	130.13	130.52	70.00
80.00	130.90	131.28	131.66	132.04	132.42	132.80	133.18	133.57	133.95	134.33	80.00
90.00	134.71	135.09	135.47	135.85	136.23	136.61	136.99	137.37	137.75	138.13	90.00
100.00	138.51	138.88	139.26	139.64	140.02	140.40	140.78	141.16	141.54	141.91	100.00
110.00	142.29	142.67	143.05	143.43	143.80	144.18	144.56	144.94	145.31	145.69	110.00
120.00	146.07	146.44	146.82	147.20	147.57	147.95	148.33	148.70	149.08	149.46	120.00
130.00	149.83	150.21	150.58	150.96	151.33	151.71	152.08	152.46	152.83	153.21	130.00
140.00	153.58	153.96	154.33	154.71	155.08	155.46	155.83	156.20	156.58	156.95	140.00
150.00	157.33	157.70	158.07	158.45	158.82	159.19	159.56	159.94	160.31	160.68	150.00
160.00	161.05	161.43	161.80	162.17	162.54	162.91	163.29	163.66	164.03	164.40	160.00
170.00	164.77	165.14	165.51	165.89	166.26	166.63	167.00	167.37	167.74	168.11	170.00
180.00	168.48	168.85	169.22	169.59	169.96	170.33	170.70	171.07	171.43	171.80	180.00

The Wheatstone Bridge

1. Unbalanced Bridge: If the two voltage dividers have exactly the same ratio (**R1/R2 = R3/R4**), then the bridge is said to be balanced and no current flows in either direction through the galvanometer. Bridge is setting to be balanced at 0 ^{o}C.

2. Balanced Bridge: An unknown resistor, R_X, is connected as the fourth side of the circuit, and power is applied. R2 is adjusted until the galvanometer, G, reads zero current. At this point, $\mathbf{R_X = R2 \times R3/R1}$.





This method is frequently used in strain gauge and resistance thermometer measurements, as it is usually faster to read a voltage level off a meter than to adjust a resistance to zero the voltage.

D. Electrical-resistance sensors

D1. Resistance thermometer (RTD) Connection

-2 Wire [Simplest]

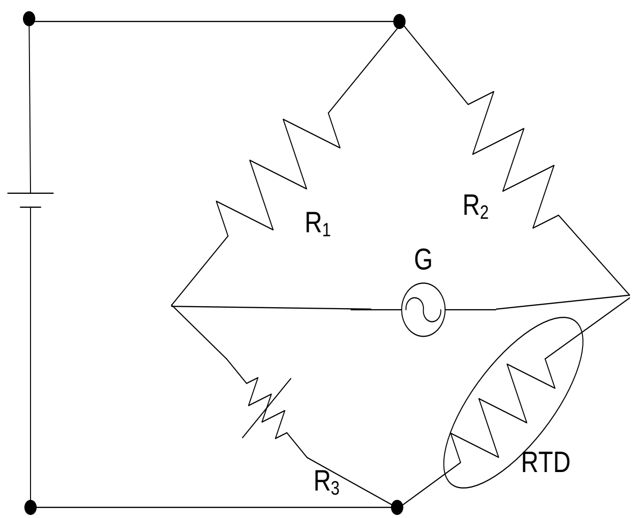
Accuracy very much depends on cable length.

Ex.

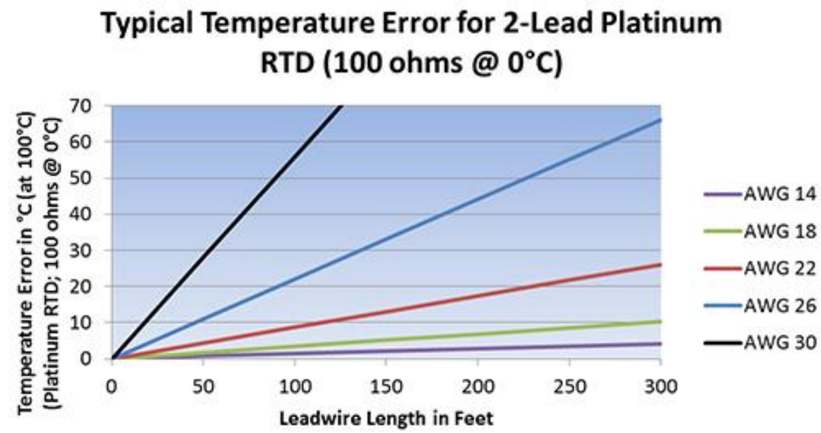
For balanced bridge, $R_1 \cdot RTD = R_2 \cdot R_3$

If $R_1 = R_2$, $R_3 = RTD$

Then $R_3 = RTD$, which measuring temperature can be found from RTD table.



Effect of the lead resistances

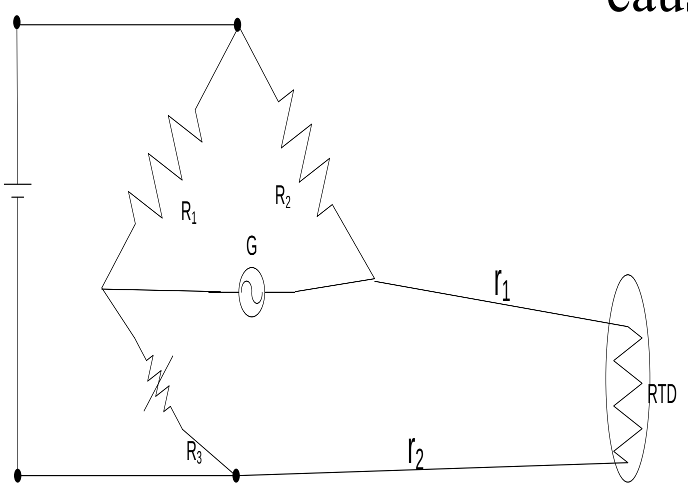


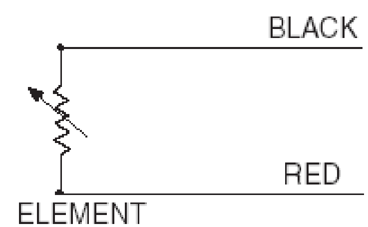
Ex. For balanced bridge,

$$R_1 \cdot (RTD + r_1 + r_2) = R_2 \cdot R_3$$

If $R_1 = R_2$,

$R_3 = RTD + r_1 + r_2$ Thus, R_3 is not only RTD. This can cause an error.





Style 1

D. Electrical-resistance sensors

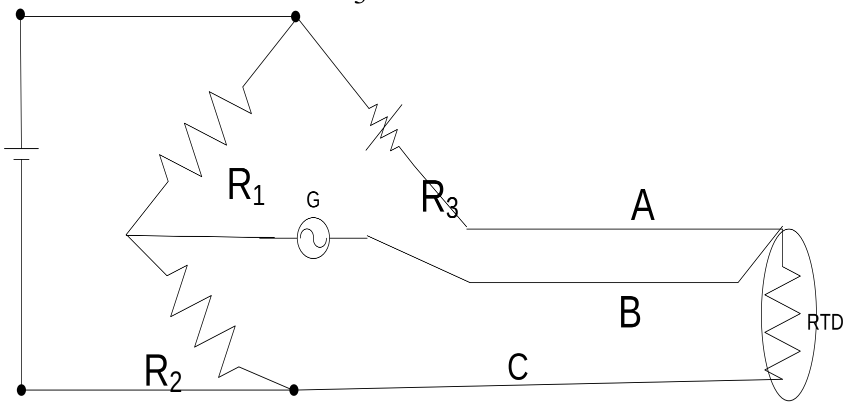
- <u>3 Wire</u> [Most popular configuration]

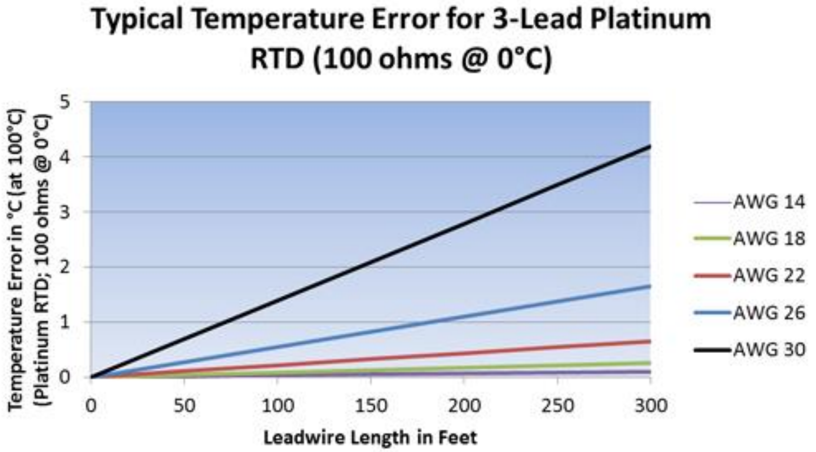
A=B=C, $R_1=R_2$ For balanced bridge,

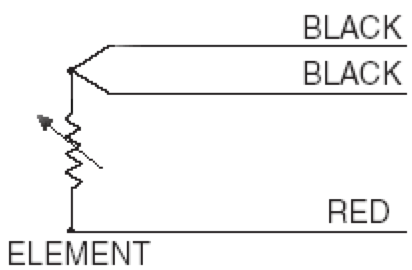
$$R_2(R_3+A) = R_1(RTD+C)$$

$$R_1 = R_2, \quad R_3+A = RTD+C$$

and A=B=C then R_3 =RTD





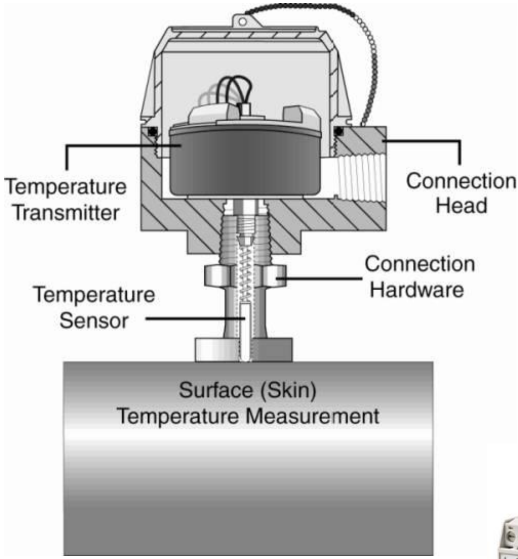


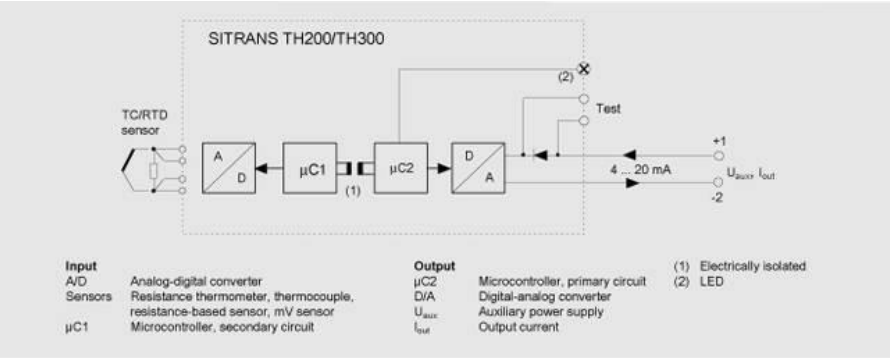
Style 2

Leadwire resistance error cancelation is most effective when all the lead wires have the same resistance. Using 3 wires of the same AWG, length, and composition will typically result in leadwire resistances matched within 5%. 3-wire construction is most commonly used in industrial applications where the third wire provides a method for removing the average lead wire resistance from the sensor measurement. When long distances exist between the sensor and measurement/control instrument, significant savings can be made in using a threewire cable instead of a four-wire cable

Reference:http://instrumentationtools.com/difference-between-2-3-and-4-wire-rtds/

Thermocouple and RTD Transmitter





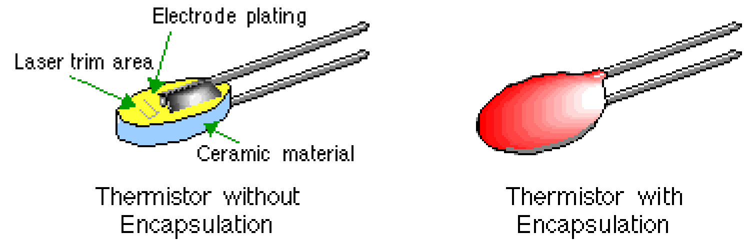
DIN rail mount

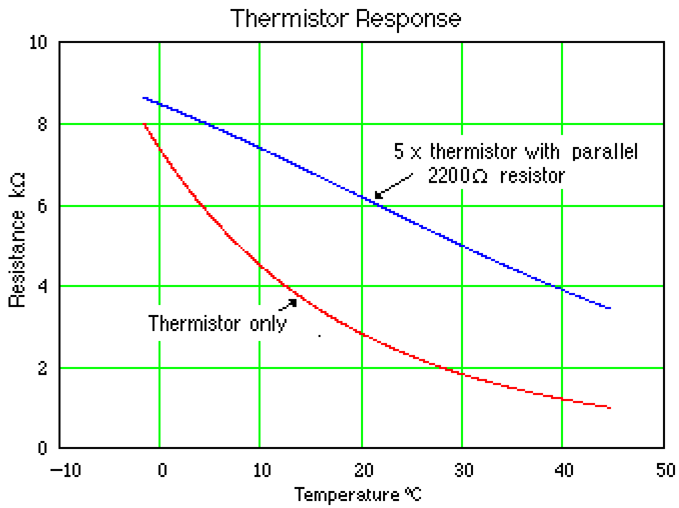
A 'Smart' Transmitter has a digital communication protocol used for reading the transmitter's measurement values and for configuring various settings in the transmitter. The most common digital communication protocols is **HART protocol**, (Highway Addressable Remote Transducer).A HART transmitter contains both a conventional analogue mA signal and a digital signal superimposed on top of the analogue signal.

Reference: http://www.processindustryforum.com/article/smart-transmitter-calibration-smart-transmitters-necessary

D. Electrical-resistance sensors

D2. Bulk Semi-conductor sensor (Thermistor)





The resistors value should equal the thermistor's resistance at the mid-range temperature. The result is a significant reduction in non-linearity. 2200 ohm resistor in parallel with a 2252 ohm (at 25◦C) thermistor.

Accurate Equations

The thermistor's resistance to temperature relationship to temperature is given by the Steinhart & Hart equation:

$$T = 1 / (a + b \cdot ln(R) + c \cdot ln(R)^3)$$

where a, b and c are constants, ln( ) the natural logarithm, R is the thermistors resistance in ohms and T is the absolute temperature in ◦K. While the Steinhart & Hart equation is a close fit to practical devices, it does not always provide the precision required over the full temperature range.

- Characteristics

- Normally high resistance, Ceramic or polymer made.
- Resistance gradient 3-5% per 1 ºC
- Positive and Negative temperature coefficient [PTC , NTC]
- Nonlinear
- higher precision within a limited temperature range, typically −90 C to 130 C

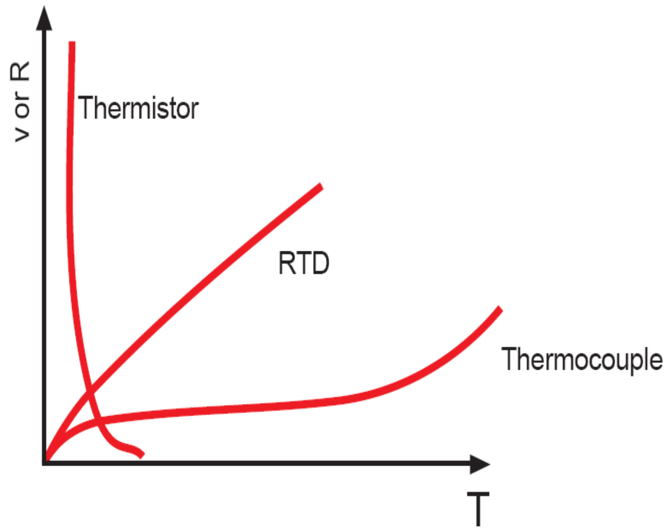
<u>Resistance-temperature relationship</u>

$$R_T = R_0 \exp B\left(\frac{1}{T} - \frac{1}{T_0}\right)$$

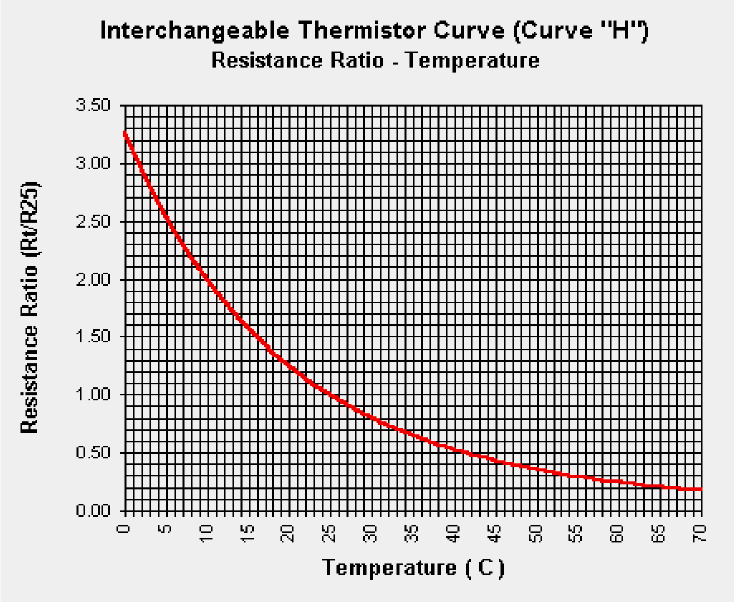
R_0 : the resistance at reference temperature i.e. T_0[K] (Ω)

R_T : the resistance of the thermistor T [K] (Ω)

B : calibration constant depending on thermistor type and material



Comparison between Temperature Sensors



Resistance Ratio vs Temperature

Temperature °C	Temperature °F	Resistance Ratio (R/R25)	Temperature °C	Temperature °F	Resistance Ratio (R/R25)
0	32	3.2657	36	97	0.6268
1	34	3.1036	37	99	0.6016
2	36	2.9505	38	100	0.5776
3	37	2.8058	39	102	0.5546
4	39	2.6690	40	104	0.5327
5	41	2.5396	41	106	0.5117
6	43	2.4174	42	108	0.4918
7	45	2.3018	43	109	0.4726
8	46	2.1922	44	111	0.4543
9	48	2.0886	45	113	0.4369
10	50	1.9904	46	115	0.4201
11	52	1.8974	47	117	0.4041
12	54	1.8093	48	118	0.3889
13	55	1.7258	49	120	0.3742
14	57	1.6465	50	122	0.3602
15	59	1.5715	51	124	0.3467
16	61	1.5003	52	126	0.3340
17	63	1.4327	53	127	0.3217
18	64	1.3684	54	129	0.3099
19	66	1.3074	55	131	0.2986
20	68	1.2495	56	133	0.2878
21	70	1.1944	57	135	0.2774

E. Junction Semi-Conductor sensors

The IC Sensor

An innovation in thermometry is the IC (Integrated Circuit) temperature transducer. These are available in both voltage and current-output configurations. Both supply an output that is linearly proportional to absolute temperature. Typical values are 1 µA/K and 10 mV/K F (Figure 45).

Some integrated sensors even represent temperature in a digital output format that can be read directly by a microprocessor.

Except that they offer a very linear output with temperature, these IC sensors share all the disadvantages of thermistors. They are semiconductor devices and thus have a limited temperature range. The same problems of self-heating and fragility are evident and they require an external power source.

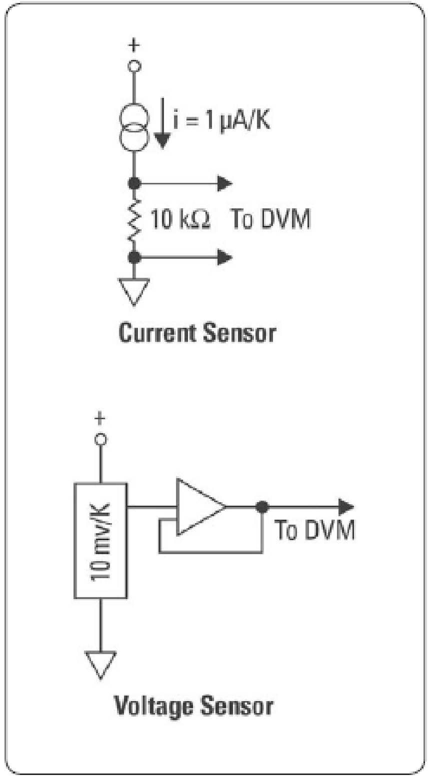


Figure 45.

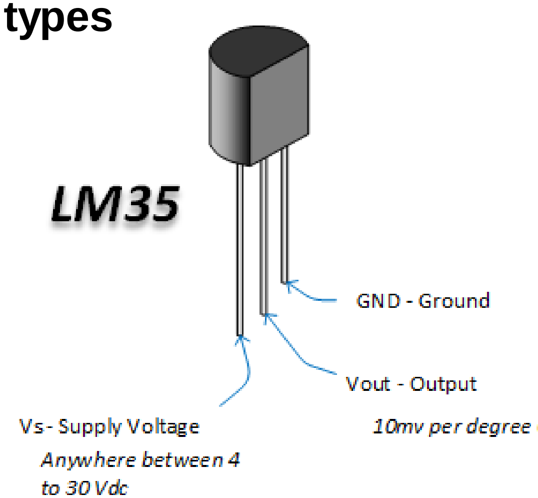
These devices provide a convenient way to produce an easy-to-read output that is proportional to temperature. Such a need arises in thermocouple reference junction hardware, and in fact these devices are increasingly used for thermocouple compensation.

A summary of available semiconductor temperatures sensors is presented below, followed by more detail on some of the more popular devices. The sensors can be grouped into five broad categories:

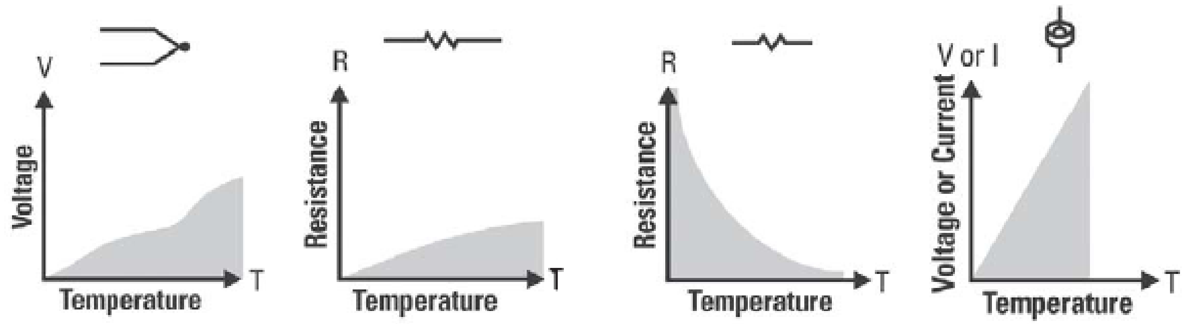
- **voltage output**
- **current output**
- **resistance output**
- **digital output**
- **simple diode types**

AD590

LM35



Comparison of Temperature Transducers



	Thermocouple	RTD	Thermistor	I. C. Sensor
Advantages	• Self-powered • Simple • Rugged • Inexpensive • Wide variety of physical forms • Wide temperature range	• Most stable • Most accurate • More linear than thermocouple	• High output • Fast • Two-wire ohms measurement	• Most linear • Highest output • Inexpensive
Disadvantages	• Non-linear • Low voltage • Reference required • Least stable • Least sensitive	• Expensive • Slow • Current source required • Small resistance change • Four-wire measurement	• Non-linear • Limited temperature range • Fragile • Current source required • Self-heating	• T<250°C • Power supply required • Slow • Self-heating • Limited configurations

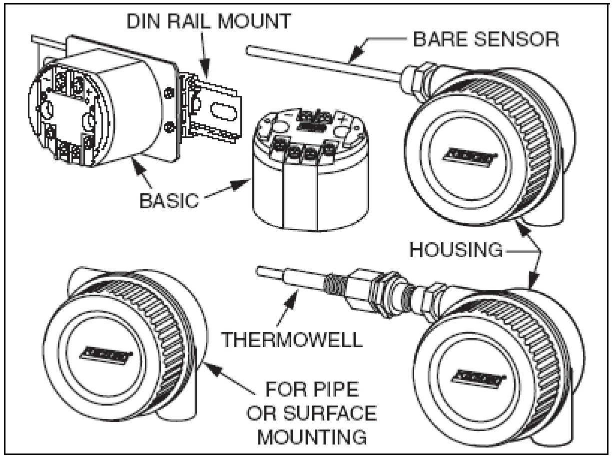
Comparison of thermocouple and RTD selection

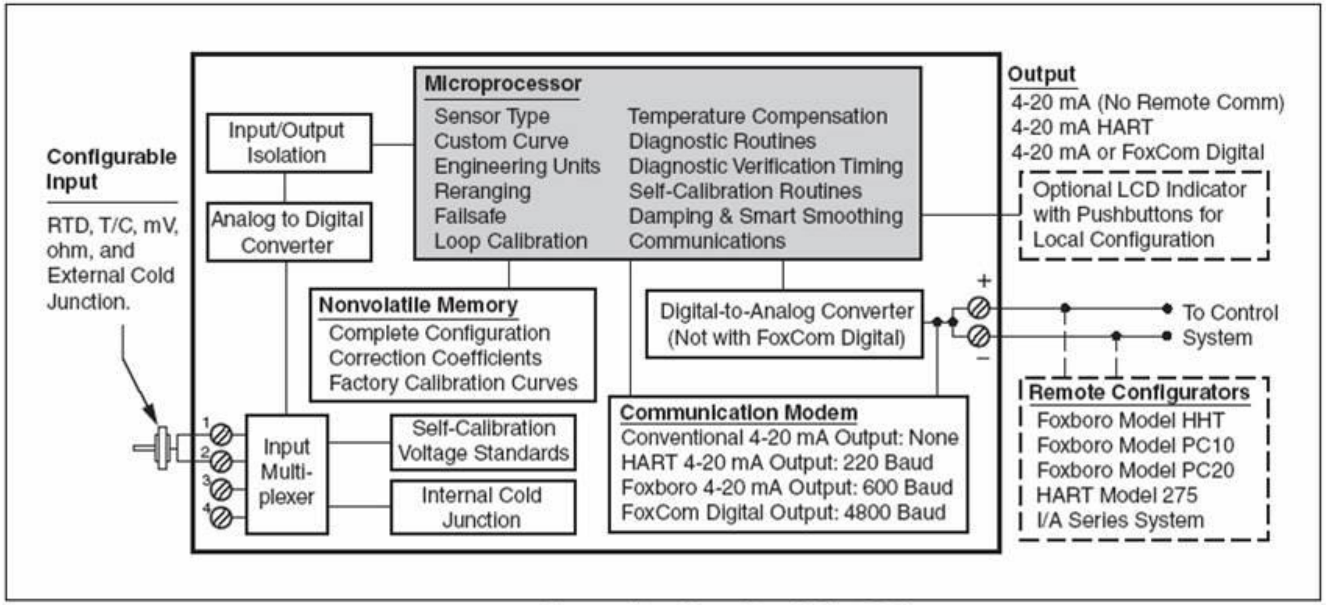
Resistance Temperature Detector (Rtd) vs. Thermocouples (General Principles)

Features	Rtd	Thermocouple
Accuracy	More Accurate	Less Accurate
Temperature Range	-200 to 600ºC	-200 to 2000ºC
Initial Cost	More Expensive	Less Expensive
Sensitivity	1" Typical (other lengths available)	Point Sensing Only
Response Time	1 to 7 seconds	less than 0.1 second
Robustness	Good	Good, Subject to drift
Reference Junction	Not Required	Required
Long Term Stability	Excellent	Good. Subject to drift
Output	Resistance 0.4 ohm/ohm/ºC Highly Linear	Voltage 10-40 microvolts/ºC, Approximately linear
Electrical Noise Resistance	Less susceptible	More susceptible

Sensor	Advantages	Disadvantages
RTD Sensor	• Linear output • Repeatability • Better stability	• Self heating • Less sensitive • Cost
Thermocouple	• Fast response • Wider temperature range • Durable	• Less accurate • Wiring is more expensive • Less stable

F. Digital Thermometer





Transmitter Functional Block Diagram

Non-contact Technologies

- The uses of noncontact temperature sensors are many; the understanding of their use is, in general, relatively poor. Part of that complication is often the need to deal with emissivity, or more precisely with spectral emissivity.
- In many industrial plants noncontact sensors are not yet standardized to the extent that thermocouples and RTDs are. In spite of this, there are numerous showcase uses of them and they more than pay their way in process plants such as steel, glass, ceramics, forging, heat treating, plastics, baby diapers and

  semiconductor operations, to name just a few.
- Non-contact sensors are required because of contamination or hazardous environments where distance are great or temperature are too high for contact sensors.

Types

- Infrared Pyrometers,
- Optical (Brightness) Pyrometer
- Others:Infrared Thermal Imaging Cameras(with temperature measurement capability), Line measuring(Line-scanner) ,(two separate waveband) Ratio Pyrometer

G. Pyrometers

Radiation pyrometers

Based on Planck's Law of the thermal emission of electromagnetic radiation , radiation pyrometers are calibrated in units of power, such as microwatts, watts,kilowatts, temperature measurement devices are calibrated in units of temperature.

Energy → Electric Signal→ Temperature

A **pyrometer** is a type of thermometer used to measure high temperature based on a thermal radiation process. A pyrometer has an optical system and detector. The optical system focuses the thermal radiation onto the detector. The output signal of the detector (Temperature T) is related to the thermal radiation of the target object through the Stefan–Boltzmann law. The output of the detector is proportional to the amount of energy radiated by the target object (less the amount absorbed by the optical system), and the response of the detector to the specific radiation wavelengths. This output can be used to infer the objects temperature.

Thermal radiation is electromagnetic radiation and it may include both visible radiation (light) and infrared radiation, which is not visible to human eyes.

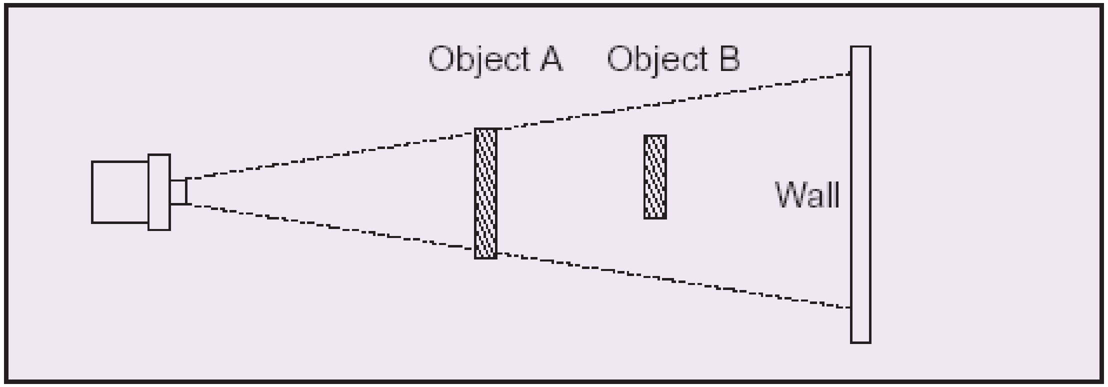
As radiation levels are influenced by the emissivity and reflection of radiation such as sunlight from the surface being measured This causes errors in the measurements. Most cameras have ±2% accuracy or worse in measurement of temperature and are not as accurate as contact methods.

Ref: https://en.wikipedia.org/wiki/Thermography

Main factors for non-contact measurement

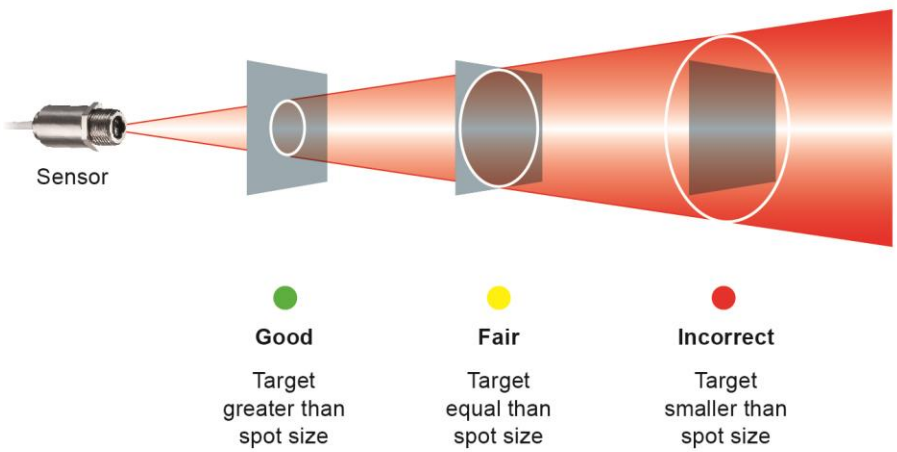
- Field of View
- Distance to Target (Spot) Ratio
- Emissivity
- Environmental Conditions
- Ambient Temperatures

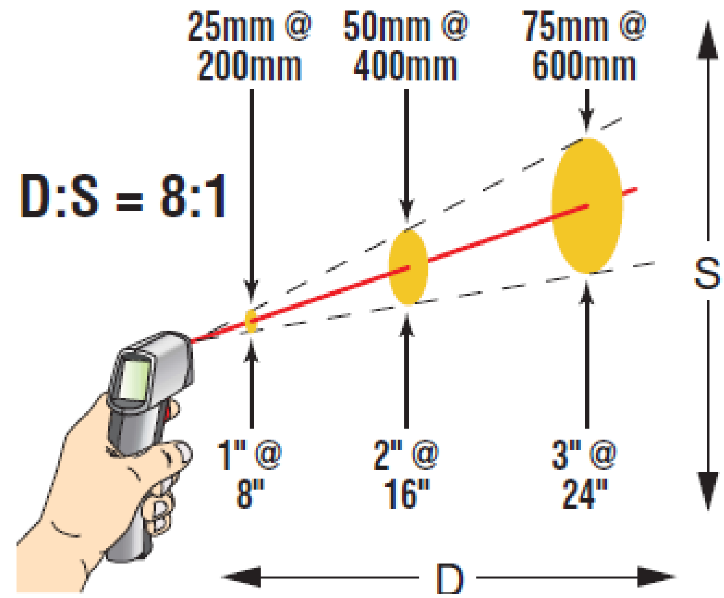
- Field of view: The field of view is the angle of vision at which the instrument operates, and is determined by the optics of the unit. To obtain an accurate temperature reading, the target being measured should completely fill the field of view of the instrument.



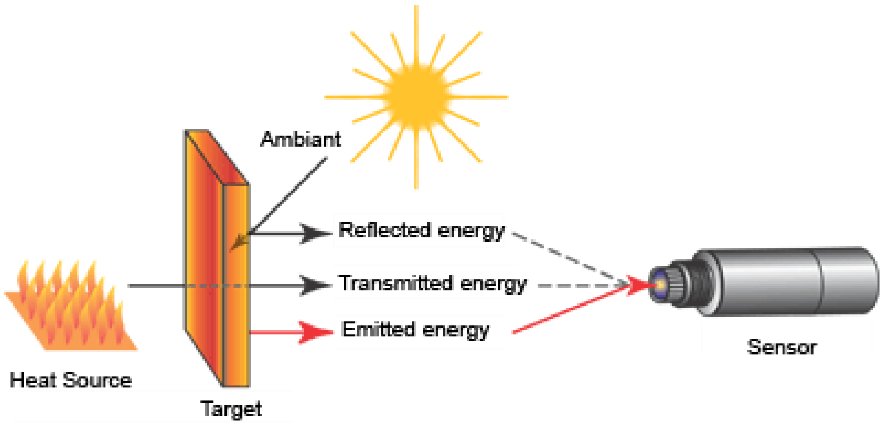
Main factors for non-contact measurement

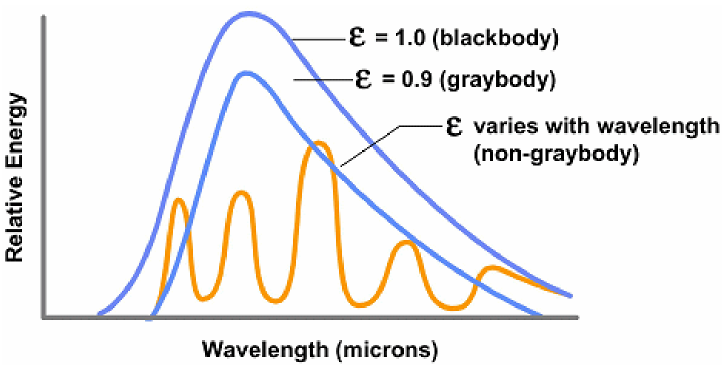
- Distance to Target (Spot) Ratio: The optical system of an infrared sensor collects the infrared energy from a circular measurement spot and focuses it on the detector. Optical resolution is defined by the ratio of the distance from the instrument to the object, compared to the size of the spot being measured (D:S ratio). The larger the ratio number the better the instrument's resolution, and the smaller the spot size that can be measured from greater distance.





- Emissivity: The emittivity, or emittance, (ϵ) of the object is an important variable in converting the detector output into an accurate temperature signal. It is defined as a ratio of the energy radiated by an object at a given temperature to the energy emitted by a perfect radiator(Blackbody ϵ=1). Emissivity is the measure of an object's ability to emit infrared energy. Emitted energy indicates the temperature of the object. Emissivity can have a value from 0 (shiny mirror) to 1.0 (blackbody).





G. Pyrometers

Infrared pyrometers

Spot Infrared Thermometer or Infrared Pyrometer, which measures the temperature at a spot on a surface (actually a relatively small area). By knowing the amount of infrared energy emitted by the object and its emissivity, the object's temperature can often be determined. Infrared thermometers are a subset of devices known as "thermal radiation thermometers“.

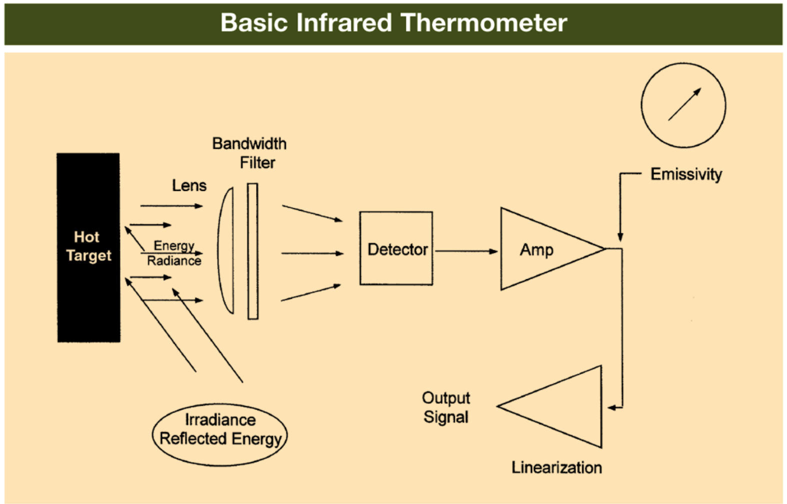
Handheld or Gun

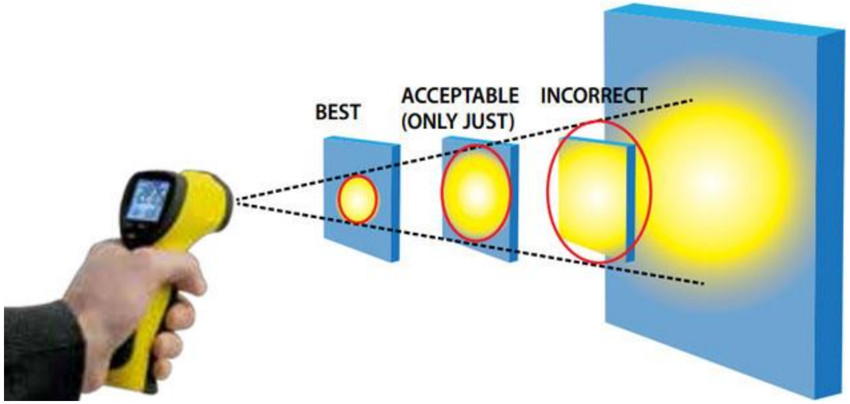
These devices can measure this radiation from a distance. There is no need for direct contact between the radiation thermometer and the object, as there is with thermocouples and resistance temperature detectors (RTDs).

Fixed-mounted

G. Pyrometers

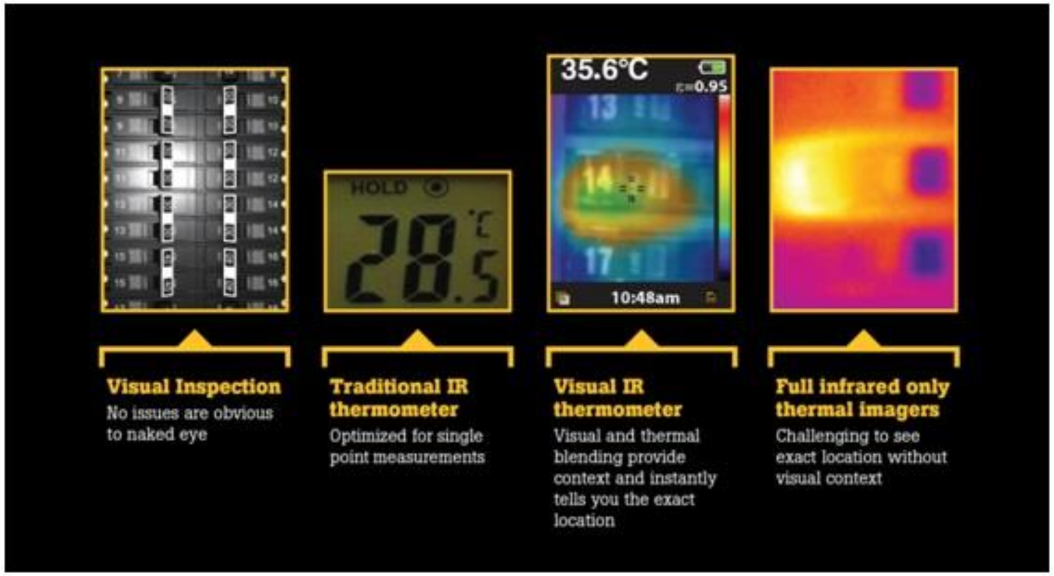
Infrared thermometer



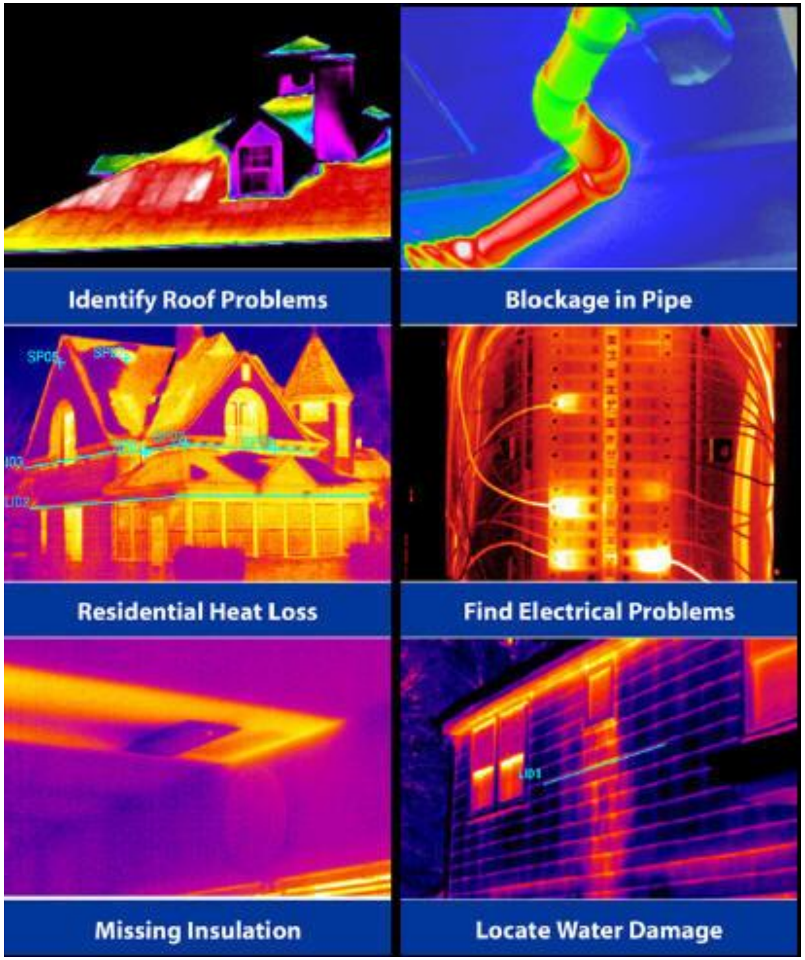


G. Pyrometers

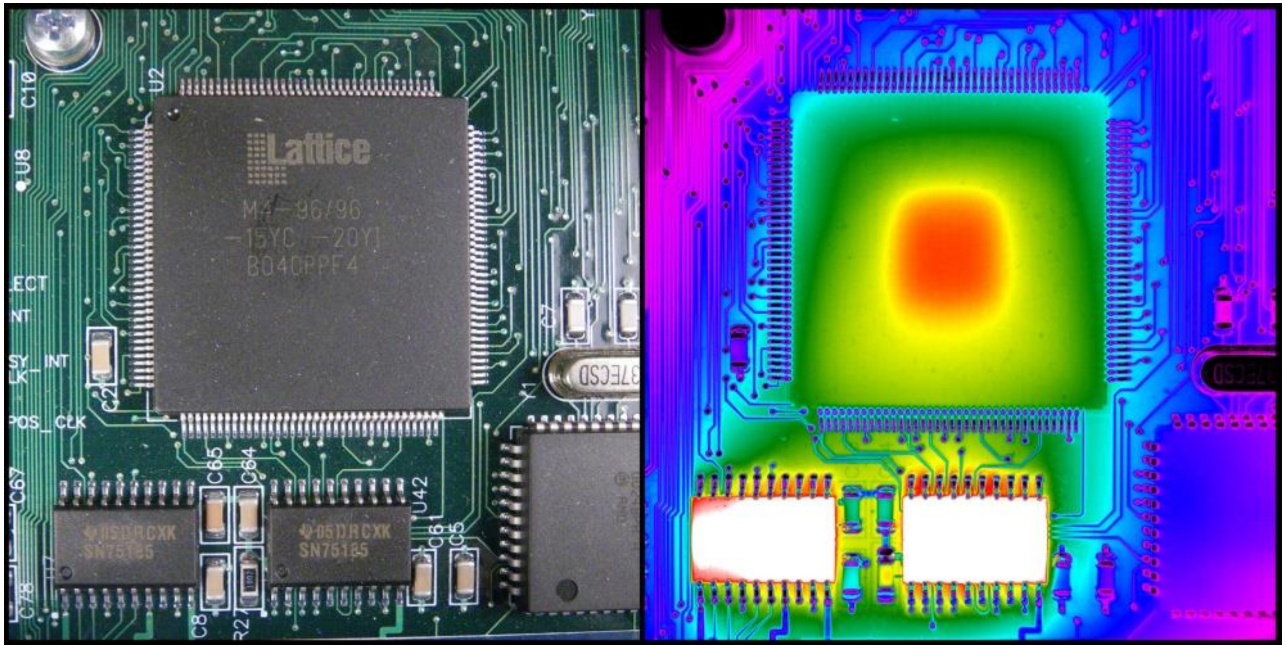
Visual IR thermometer

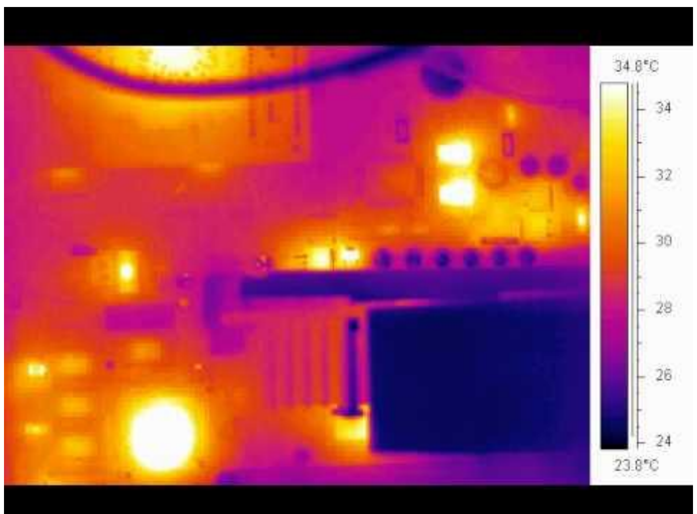


Others:Thermal Imaging Camera

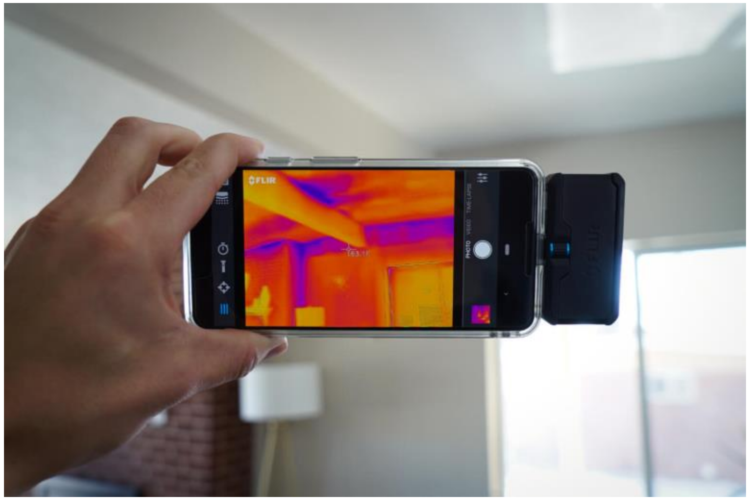


Applications





CPU motherboard



House inspection

Body Temperature for fever screening

Calibration radiators

Black body radiation sources for calibration and testing of infrared radiation pyrometer, LINE-SCANNER and thermal imager

SUMMARY AND CONCLUSION