Temperature Measurements

Temperature Measurements

- **Measure of hotness or coldness of a body**
- **Usually measured by observing the change in another temperature dependent property.**
- **No direct comparison**
- **References are established from the physical, thermo-physical and electrical properties of the substances.**

Contact: **Two are in thermal equilibrium (physical contact)**

Non-Contact: **Measure the thermal radiant power of the Infrared or Optical radiation that they receive from a known or calculated area on its surface**

Temperature measurement units

- $°F = (9/5 \times °C) + 32$
- $°C = 5/9 \times (°F - 32)$
- $K = °C + 273$

Common Temperature Reference Points

	Fahrenheit	Celsius	Kelvin
Absolute Zero	-460	-273	0
Liquid Helium (boiling)	-452.1	-268.8	4.2
Liquid nitrogen (boiling)	-321	-196	77
Water (freezing)	32	0	273
Water (boiling)	212	100	373
Freezing point of Zn	787.2	419.58	692.58
Freezing point of silver	1763.5	961.93	1234.93
Freezing point of gold	1947.98	1064.43	1337.43

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Types of Temperature Measurements

Change in Physical Properties	Changes in Chemical Properties
- Bimetallic Thermometers - Liquid-in-Glass thermometers - Pressure thermometers	- Quartz crystal thermometry - Temperature sensitive paints
Changes in Electrical Properties	**Change in Emitted thermal radiation**
- Resistance Temperature Detectors (RTDs) - Thermisters - Thermocouples (TCs) - IC sensors	- Radiation & infrared pyrometers

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Bimetallic Temperature Measurement Devices

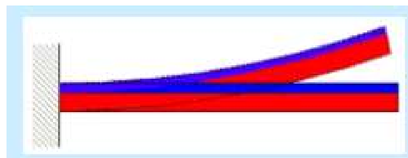
Working based on the difference in rate of thermal expansion.

Strips of two metals (different thermal expansion coefficient) are bonded together. When heated, one side will expand more than the other, and the resulting bending is translated into a temperature reading by mechanical linkage to a pointer.

These devices are portable and they do not require a power supply, negligible maintenance, stable operation but they are usually not as accurate as thermocouples or RTDs and they do not readily lend themselves to temperature recording.

Invar, Nickel for low thermal expansion 0.0000017 mm/^{o}C

SS, Brass, Cu, Al for high expansion



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$$R = \frac{t\left\{3(1+m)^2 + (1+mn)[m^2 + (1/mn)]\ \right\}}{6(\alpha_2 - \alpha_1)(T - T_0)(1+m^2)}$$

R = radius of curvature

t = combined thickness of the bonded strip, m (< 3.73 mm)

m = ratio of thickness of low and high expansion materials (t_1/t_2)

n= Modulus ratio (E_1/E_2)

α_1, α_2 higher and lower coefficient of thermal expansion, per ^{o}C

T= measurement temperature, ^{o}C

T_o = Initial bonding temperature, ^{o}C

In most cases, t_1/t_2 =1 and n + 1/n = 2 giving

$$\boldsymbol{R} = \frac{2\boldsymbol{t}}{3(\alpha_2 - \alpha_1)(\boldsymbol{T} - \boldsymbol{T}_0)}$$

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BIMETALIC THERMOMETER

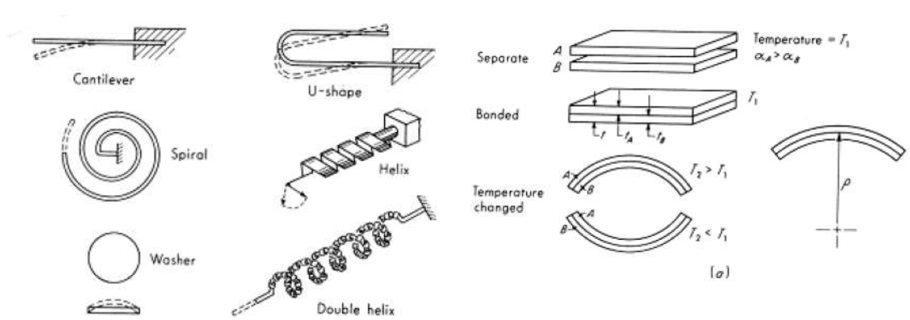
- Range: - 65 °C to 430 °C
- Accuracy: ± 0.5 to 1 % of scale range

Advantages

- Low cost
- Negligible maintenance
- Stable operation over time

Application: Thermal Cut – off Relay (thermostats), overload cutout switches, temperature compensating devices

Types of BM Thermometer



Source: E.O.Doebelin, Measurements systems.

Table: Properties of some commonly used thermal materials

Material	Th. Coefficient of Expansion /°C	E (GN/m^2)
Invar	1.700×10^{-6}	147.0
Yellow Brass	2.02×10^{-5}	96.5
Monel 400	1.35×10^{-5}	179.0
Inconel 702	1.25×10^{-5}	217.0
316 SS	1.60×10^{-5}	193.0

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Fluid-Expansion Temperature Measurement Devices

Thermal expansion of liquid.

Mercury filled thermometers

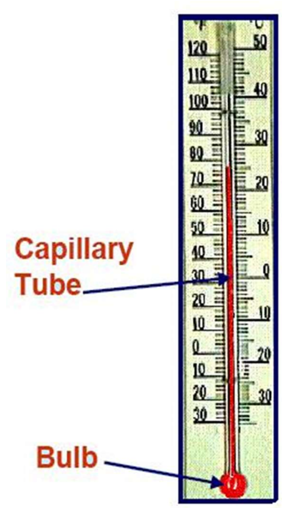
- Range: -39 to ~ 540 °C
- Accuracy ± 0.3 °C

Alcohol Filled thermometers

- Range: -75 to ~ 1200 °C
- Accuracy ± 0.6 °C

Advantages and Disadvantages

- Low cost
- Difficult to remote operation
- Lower/upper limits determined by the freezing and boiling points.



Glass in Mercury Thermometer

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- **Mercury Glass thermometer can not be used**
  - **below –37.8°C and above 538°C**
- **Temperature measurement is based on the difference between the expansion of the liquid and the expansion of the glass. The difference is a function of the heat transfer to the bulb from the environment and also heat conducted into the bulb from the stem.**

  Less stem conduction is preferable.
- **Special marking for depth to be immersed is required.**

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Desirable properties of the liquid

- **Should have linear expansion**
- **Liquid should have large coefficient of expansion (for high sensitivity)**
- **The liquid should accommodate a reasonable temperature range without change of phase**
- **Liquid should be clearly visible when drawn into a fine capillary.**
- **Liquid should not stick to the glass**
- **Should have high thermal conductivity (For better response)**

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About Glass-Liquid Thermometer

- **Fluid-expansion sensors do not require electric power, do not pose explosion hazards, and are stable even after repeated cycling.**
- **On the other hand, they do not generate data that can be easily recorded or transmitted, and they cannot make spot or point measurements.**
- **Not used for dynamic measurements**

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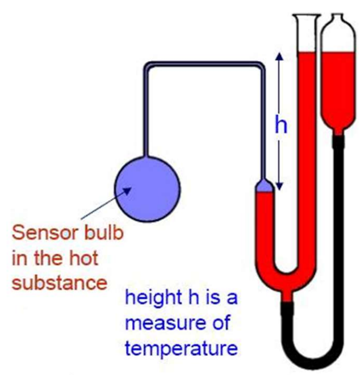
Pressure Thermometer

Liquid, Gas and combination of liquid and gas

- A fluid filled bulb is connected to a pressure measuring device such as a manometer, Bourdon tube, bellows, etc., via a capillary tube. As fluid is heated it expands; thus pressure increases.
- Pressure change at constant volume.
- Liquid filled systems.
- -150 to 750^{0}F with xylene.



High response is obtained with smaller bulb and short capillary with electric pressure transducer.

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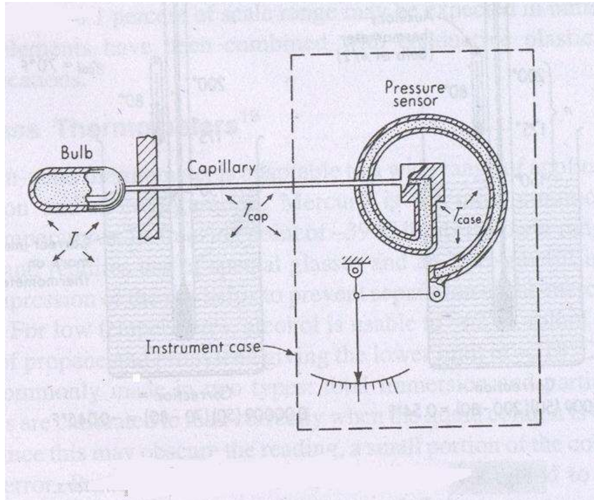

Capillary length up to 60 m
-39 to 590^{o}C with Hg
Gas filled -240 to 540^{o}C

Pressure thermometer

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Advantages / Disadvantages

- Low cost
- Stable in operation
- Simple, so widely used in industrial applications
- Remote readings are possible
- Response is a function of bulb volume and capillary tube dimensions.

A commercial version

Accuracy ± 1.5^{o}C

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Resistance Temperature Detector (RTD)

The resistance rising more or less linearly with temperature. Thin platinum wire, which has positive temperature coefficient.

$$R(T) = R_{ref}(1 + a(T - T_{ref}) + b(T - T_{ref})^2)$$

R(T) = Resistance at T, R_{ref} = Resistance at reference point
a and b temperature coefficients of resistance depending on material.

Over a limited temperature interval a linear approximation to the resistance variation may be quite acceptable

$$\boldsymbol{R(T) = R_0[1 + A(T - T_o)]}$$

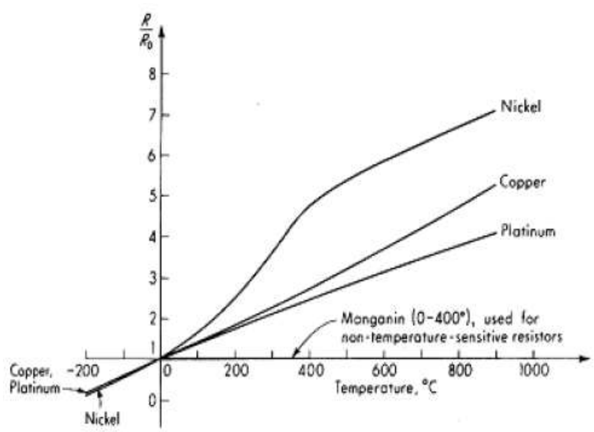
For higher accuracy, higher order polynomial fit is requied

$$\boldsymbol{T = b_o + b_1\left[\frac{R}{R_{ref}}\right] + b_2\left[\frac{R}{R_{ref}}\right]^2 + \ldots\ldots + b_n\left[\frac{R}{R_{ref}}\right]^n.}$$

where, $\boldsymbol{b_0 + b_1 + \ldots\ldots + b_n = T_{ref}}$

$$\alpha = \frac{\boldsymbol{R_2 - R_1}}{\boldsymbol{R_1(T_2 - T_1)}}$$

$$\alpha = \frac{\boldsymbol{R_2 - R_1}}{\boldsymbol{R_1(T_2 - T_1)}}$$



- **Copper for low temperature range**
- **Platinum is linear**
- **Nickel for both low and high temperature (Linearity is obtained by alloying with other elements**

Advantages of RTD

- Low resistance
  - 100 Ω (most common) to 1000 Ω
- Wide operating range -260 to 1000°C with platinum
- High sensitivity
  - (compared to thermocouples)
- High accuracy ± 0.1 to 1.5°C
- High Repeatability and Stability
  - Low drift (0.0025 °C/year)
  - Industrial models drift < 0.1 °C/year

-200 to 450°C with Ni

Different range may be possible with variable R circuit

Disadvantages of RTD

- Lead wire resistance can be significant.
- Slower response time
- Fragile - Sensitive to shock and vibration
- Internal/self-heating (I^2R).

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THERMISTORS

- The resistance drops (respond inversely with temperature) nonlinearly with temperature rise.
- Ceramic and some semiconductor, which have negative temperature coefficient

$$R(T) = R_{ref}\exp\left[\beta\left(\frac{1}{T} - \frac{1}{T_{ref}}E\right)\right]$$

$$\frac{1}{T} = \frac{1}{T_{\mathrm{Ref}}} + \frac{1}{\beta}\left[\ln(R) - \ln(R_{\mathrm{Ref}})\right]$$

$$\Rightarrow T = \frac{T_{\mathrm{Ref}}\cdot\beta}{\beta + T_{\mathrm{Ref}}\left[\ln(R) - \ln(R_{\mathrm{Ref}})\right]}$$

β = 3,000 to 4,600 K

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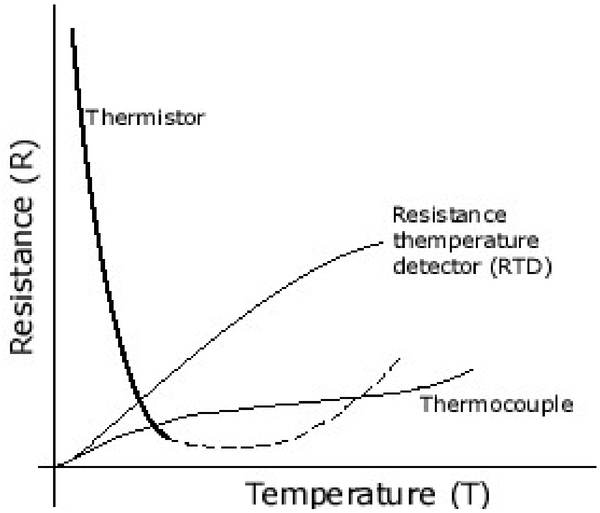
Advantages of Thermistor

- High accuracy, ~±0.02 °C (±0.36°F), better than RTDs, much better than thermocouples.
- High sensitivity, ~10 times better than RTDs, much better than thermocouples. As a result, lead wire and self-heating errors are negligible.
- Small in size compared to thermocouples.
- Response time shorter than RTDs, about the same as thermocouples. Reasonable long term stability and repeatability.

Disadvantages

- Limited temperature range, typically -100 to 150 °C (-148 to 302 °F).
- Nonlinear resistance-temperature relationship, unlike RTDs which have a very linear relationship.

Sensitivity ± 6 mV/°C
Silicon with x % of Boron
Germanium doped arsenic, gallium, arsenic for cryogenic temp.



Comparison between thermocouple, RTD and Thermistor

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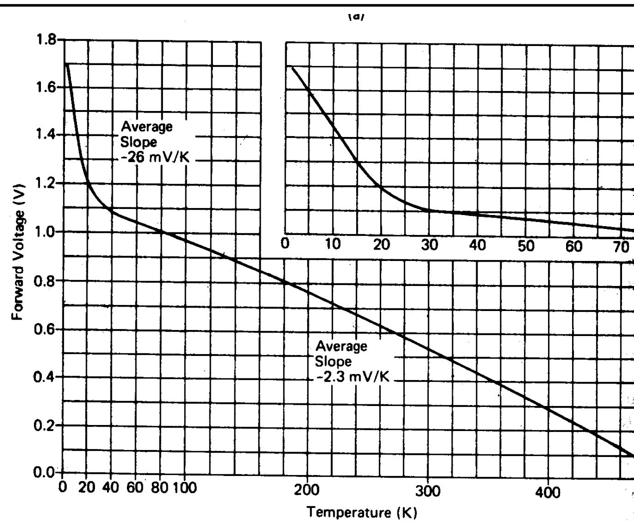
Semi Conductor / IC Temperature sensors

When a diode is powered with a fixed current of about 10 μA, and the resulting forward voltage is inversely proportional to the temperature of the environment.

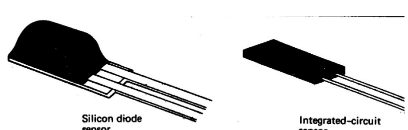
- **Operating ranges maximum about -220 to 200°C.**
- **Accuracy = ± 0.5°C**
- **Much cheaper**
- **Good sensitivity**
- **Very small in size**
- **Has good linear characteristics between temperature and forward voltage**



Temperature Voltage Relationship

Silicon

Gallium – Aluminum - Arsenide

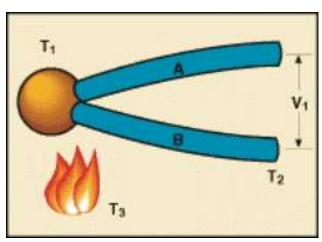


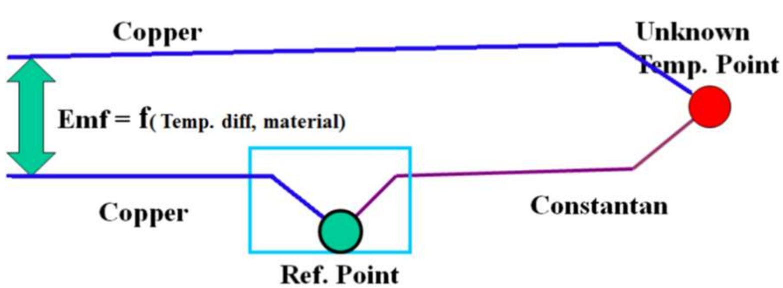
Low temperature measurements.

THERMOCOUPLES

- **Most commonly used passive method of temperature measurement**
- **Works based on the principle of Seebeck Effect**
- **Thermocouples consist essentially of two wires made of different metals.**
- **When two dissimilar metals are physically joined to form a junction, and the two junctions are kept at different temperatures an emf develops in the circuit.**
- **Usually one junction is kept at a reference point (temperature) and the other one is kept at the environment where the temperature is to be measured.**

Principle of Operation





- Changes in the temperature at that juncture induce a change in electromotive force (emf) between the other ends.
- As temperature goes up, this output emf of the thermocouple rises, though not necessarily linear.
- Induced emf depends on the material as well as temperatures of the junctions.
- Basically TCs are inexpensive, small in size, passive type and offer good accuracy if properly used.

$$\alpha_{AB} = \left[\frac{\partial(emf)}{\partial T}\right]_{open\ circuit}$$

The Seebeck coefficient is defined as the open circuit voltage produced between two points on a conductor, where a uniform temperature difference of 1K exists between those points.

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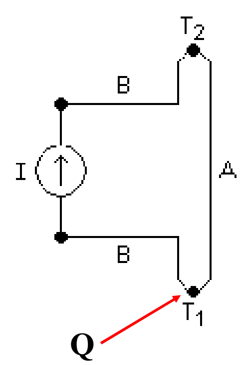
Peltier Effect

Peltier Effect: Describes thermal effects at the junctions of dissimilar conductors when an electrical current flows between the materials. i e. Cooling and heating at the junctions of two dissimilar metals occur when an electrical current is passed through the circuit.



The current drives a transfer of heat from one junction to the other: one junction cools while the other heats up. The effect is often used for THERMOELECTRIC COLLING

$$\dot{Q} = \Pi_{AB} I$$

Where Π_{AB} the Peltier coefficient of the entire thermocouple

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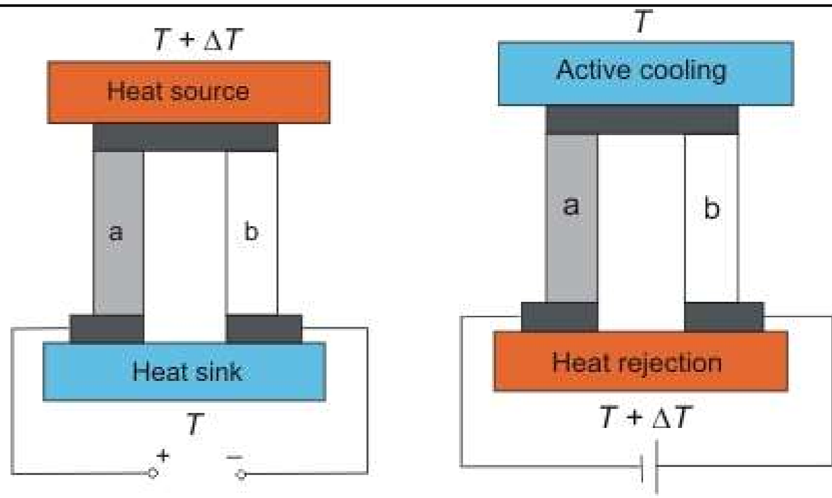

Seebeck Effect

Power generation

Peltier Effect

Cooling application

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Seebeck emf : **Caused mainly due to the junction of dissimilar metals**

Peltier emf: **caused by a current flow in the circuit**

- **Peltier heating and cooling effects are negligible, in the case no current flow in the circuit**
- **Seebeck emf is the prime concern because its mainly depends on the junction temperature.**
- **Proper correlation between emf and the temperature difference between the junctions are obtain only by the experiments.**

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Construction of TCs

- Metals are classified as positive metals and negative metals based on the free electron motion behaviour.
- A dissimilar metal pair (TC) is constructed with one positive metal and one negative metal.
- A TC is named after the name of the positive and negative metals in that order.
- Eg: Copper-Constantan thermocouple

(+ve metal) (-ve metal)

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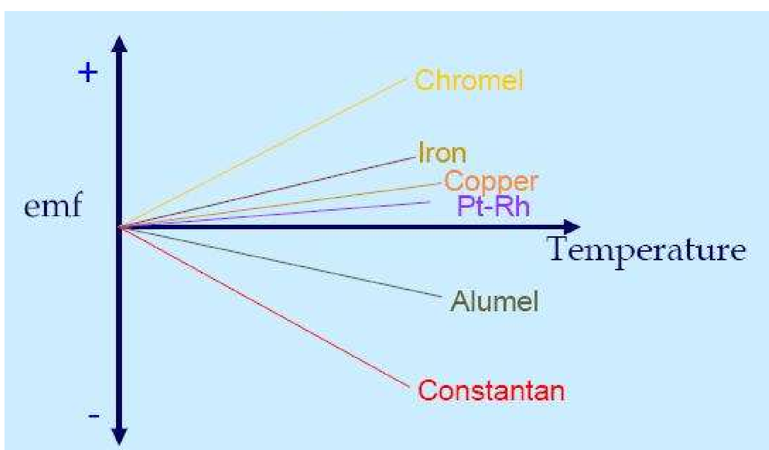
Material emf



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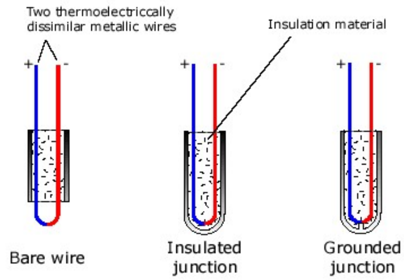
Types of TCs Beads



- **Exposed or bare end**
- **Insulated or ungrounded end**
- **Grounded end**

Exposed or Bare End: **Junction is completely exposed to the surrounding environment. Best response time, but limited to non-corrosive applications**

Ungrounded End: **Junction is detached from the probe. Electrical isolation is obtained at the cost of response time**

Grounded End: **Junction is physically attached to the probe wall. Good heat transfer to the junction.**

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TC Junctions

- Thermojunctions formed by welding, soldering, or merely pressing the two materials together.
- Welding - either gas or electric.
- Both silver solder and soft solder are used in copper/constantan couples.

Twisted Junction

Welded Junction

Soldered Junction

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Types of thermocouples and their operating ranges

Type	Material	Temp. range	Sensitivity µV/ °C	Error
E	Chromel & Constantan (Ni-Cr & Cu-Ni)	-100~1000	60.9	LT:± 1.67°C HT:± 5%
J	Iron & Constantan (Fe & Cu-Ni)	0~1200	51.7	LT:± 2.2~1.1°C HT:± 0.375~0.75%
K	Chromel & Alumel (Ni-Cr & Ni-Al)	-0~1350	40.6	LT:± 2.2~1.1°C HT:± 0.375~0.75%
T	Copper & Constantan (Cu & Cu-Ni)	-160~400	40.6	LT:±1.2°C HT:±1.5% or ±0.42°C
R	Platinum & 87% Platinum/ 13% Rhodium (Pt & Pt-Rh)	0~1500	6	LT: ± 2.8°C HT: ± 0.5%
S	Platinum & 90% Platinum/ 10% Rhodium (Pt & Pt-Rh)	-0~1750	6	LT: ± 2.8°C HT: ± 0.5%
B	70% Platinum/ 30% Rhodium & 94% Platinum/ 6% Rhodium (Pt-Rh & Pt-Rh)	-50~1750	6	LT: ± 2.8°C HT: ± 0.5%

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Emf verses Temperature for different TCs

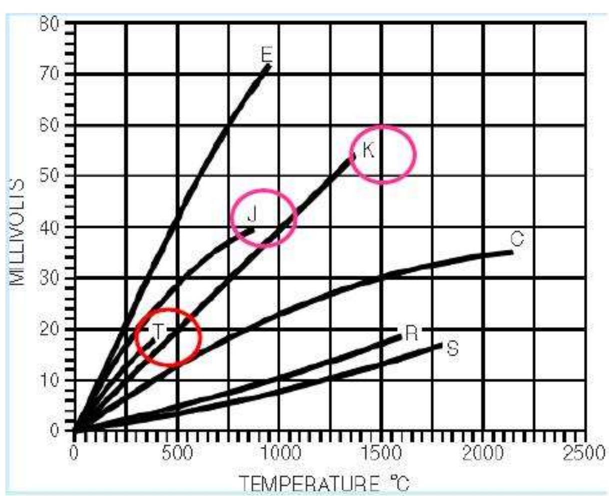

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Table 8.3a Thermal emf in absolute millivolts for commonly used thermocouple combinations, according to ITS(90) (Reference junction of 0°C)†

Temperature, °C	Copper vs. Constantan (*T*)	Chromel vs. Constantan (*E*)	Iron vs. Constantan (*J*)	Chromel vs. Alumel (*K*)	Platinum vs. Platinum–10% Rhodium (*S*)	Nicosil vs. Nisil (*N*)
−150	−4.648	−7.279	−6.500	−4.913		−1.530
−100	−3.379	−5.237	−4.633	−3.554		−1.222
−50	−1.819	−2.787	−2.431	−1.889	−0.236	−0.698
−25	−0.940	−1.432	−1.239	−0.968	−0.127	−0.368
0	0	0	0	0	0	0
25	0.992	1.495	1.277	1.000	0.143	0.402
50	2.036	3.048	2.585	2.023	0.299	0.836
75	3.132	4.657	3.918	3.059	0.467	1.297
100	4.279	6.319	5.269	4.096	0.646	1.785
150	6.704	9.789	8.010	6.138	1.029	2.826
200	9.288	13.421	10.779	8.139	1.441	3.943
300	14.862	21.036	16.327	12.209	2.323	6.348
400	20.872	28.946	21.848	16.397	3.259	8.919
500		37.005	27.393	20.644	4.233	11.603
600		45.093	33.102	24.906	5.239	14.370
800		61.017	45.494	33.275	7.345	20.094
1000		76.373	57.953	41.276	9.587	26.046
1200			69.553	48.838	11.951	32.144
1500					15.582	
1750					18.503	

†Composition of Thermocouple Alloys:
Alumel: 94% nickel, 3% manganese, 2% aluminum, 1% silicon
Chromel: 90% nickel, 10% chromium
Constantan: 55% copper, 45% nickel
Nicosil: 84% nickel, 14% chromium, 1.5% silicon
Nisil: 95% nickel, 4.5% silicon, 0.1% Mg

Holman, Ex. Methods for Engr.

T type thermocouples can not be used above 350°C, the oxidation of copper above this range.

R and S type is meant for high temperature up to 1400°C, due its chemical inertness and stability in oxidizing atmosphere.

Table 8.5 Polynomial coefficients for Eq. (8.12) for several standard thermocouple combinations

	Type E	Type J	Type K	Type R	Type S	Type T
	Chromel(+) vs. Constantan(−)	Iron(+) vs. Constantan(−)	Chromel(+) vs. Nickel-5%(−) (Aluminum Silicon)	Platinum-13% Rhodium(+) vs. Platinum(−)	Platinum-10% Rhodium(+) vs. Platinum(−)	Copper(+) vs. Constantan(−)
	−100°C to 1000°C* ±0.5°C 9th Order	0°C to 760°C* ±0.1°C 5th Order	0°C to 1370°C* ±0.7°C 8th Order	0°C to 1000°C* ±0.5°C 8th Order	0°C to 1750°C* ±1°C 9th Order	−160°C to 400°C* ±0.5°C 7th Order
a_0	0.104967248	−0.048868252	0.226584602	0.263632917	0.927763167	0.100860910
a_1	17189.45282	19873.14503	24152.10900	179075.491	169526.5150	25727.94369
a_2	−282639.0850	−218614.5353	67233.4248	−48840341.37	−31568363.94	−767345.8295
a_3	12695339.5	11569199.78	2210340.682	1.90002E+10	8990730663	78025595.81
a_4	−448703084.6	−264917531.4	−860963914.9	−4.82704E+12	−1.63565E+12	−9247486589
a_5	1.10866E+10	2018441314	4.83506E+10	7.62091E+14	1.88027E+14	6.97688E+11
a_6	−1.76807E+11		−1.18452E+12	−7.20026E+16	−1.37241E+1	−2.66192E+13
a_7	1.71842E+12		1.38690E+13	3.71496E+18	6.17501E+17	3.94078E+14
a_8	−9.19278E+12		−6.33708E+13	−8.03104E+19	−1.56105E+19	
a_9	2.06132E+13				1.69535E+20	

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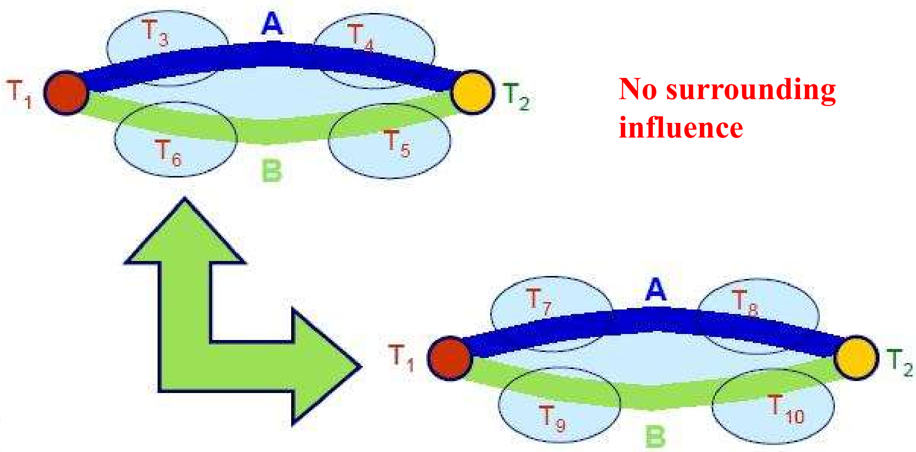
Holman, Ex. Methods for Engr.

Thermocouples Laws – No.1

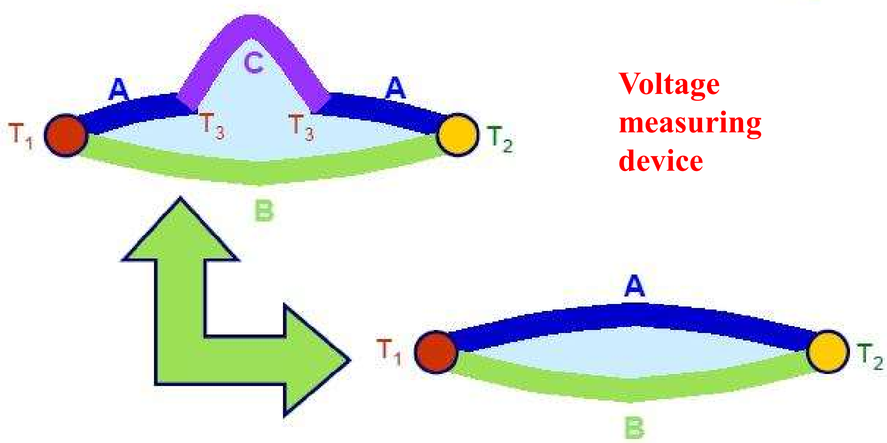
Thermal emf is totally unaffected by temperature elsewhere in the circuit.



No surrounding influence

Thermocouples Laws – No.2

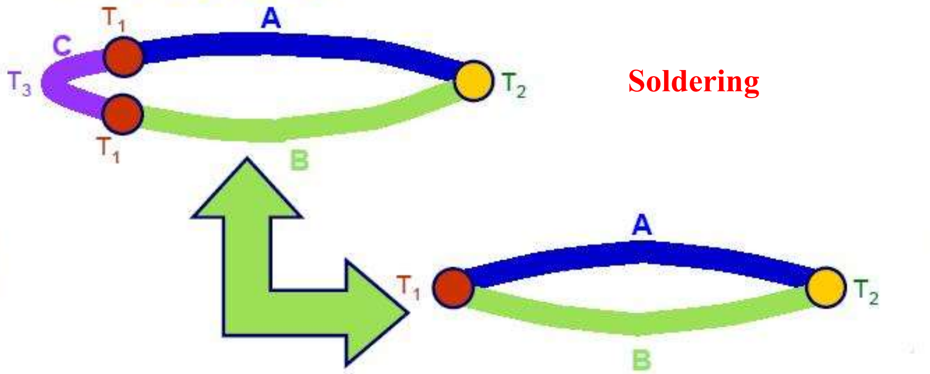
If a third homogeneous metal *C* is inserted into either *A* or *B*, net emf is unchanged.



Voltage measuring device

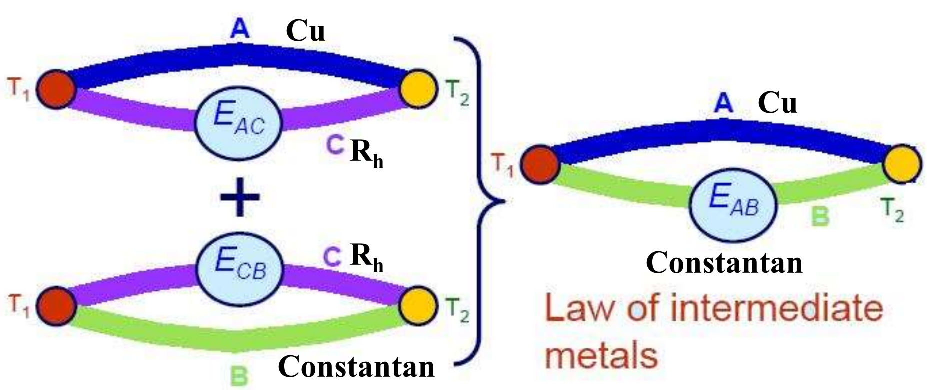
Thermocouples Laws – No.3

If metal C is inserted at one of the junctions, as long as the junctions AC and BC are at the same temperature T_1, the net emf is the same as if C were not there.



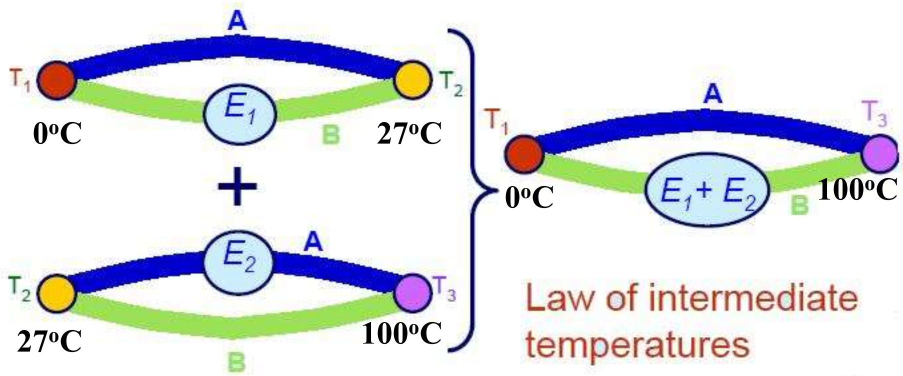
Thermocouples Laws – No.4

If thermal emf of A and C is E_{AC}, B and C is E_{CB}, A and B is $E_{AC} + E_{CB}$.



Thermocouples Laws – No.5

If a thermocouple produces emf E_1 when its junctions are at T_1 and T_2, and E_2 when at T_2 and T_3, it will produce E_1+E_2 when the junctions are at T_1 and T_3.



Implications of TC Laws

- Lead wires connecting the two junctions may be safely exposed to an unknown and/or a varying temperature environment (Law 1)
- Law 2 enables us to insert a voltage-measuring device into the circuit actually to measure the emf.
- Law 3 shows that thermocouple junctions may be soldered or brazed.
- Law 4 shows that all possible pairs of metals need not be calibrated since the individual metals can each be paired with one standard.
- Fifth law allows use of the standard table (Reference junction being at ice point).

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Special Precautions

- There may be precautions specific to certain TCs. For example,
- Iron – constantan can generate a galvanic emf in the presence of water, so it should not be used where it might get wet.
- Chromel-Alumel can generate electric signals in stressed condition (eg while being bent) and should not be used on vibrating systems.
- In some Chromel-Alumel TCs, silver solders and special fluxes must be used.
- Using grounded thermocouples may cause erroneous reading due to ground loops. Electrically isolation can be obtained by using MgO packing material.

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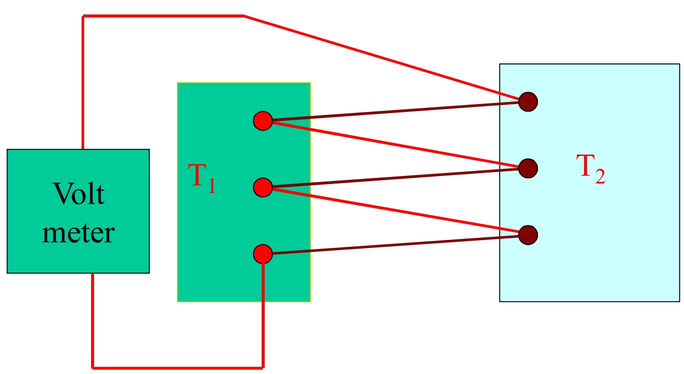
Thermopile

Thermocouples are connected in series between the same two temperature zones.

- **Used for determining the small temperature differences**
- **It gives an amplified emf**



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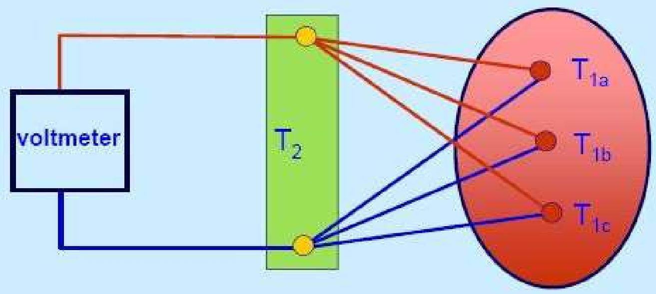
Averaging Circuit

- Thermocouples are connected in parallel between two temperature zones, where the average temperature of a zone with spatial variation of temperature is desired



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High Temperature applications

- **Application like jet propulsion engine, nuclear reactor, etc.**
- **Boron – Graphite – 2500°C with 40 μV/°C**
- **Rhodium – Iridium - 2200°C with 6 μV/°C**
- **Zr – Rhenium - 2700°C about 6 μV/°C**

How do measure the temperature in the range of 3000 - 4500°C with acceptable accuracy?

Pulse cooling thermocouples

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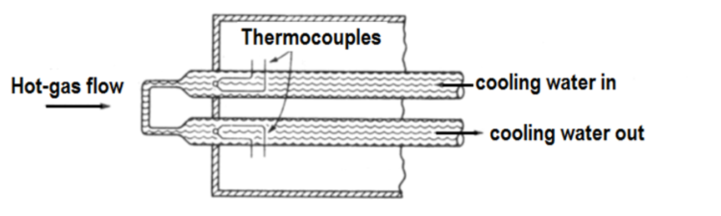
Special techniques



The hot gas (whose temperature is t0 be measured) impinges on a small tube carrying cooing water, causing a temperature rise of about 55°C.

The hot gas temperature is determined by knowing

- **heat transfer coefficients**
- **water flow rate**
- **inlet water temperature and**
- **rise in water temperature.**

Source: Action instruments Inc., San Diego. www.actionio.com)

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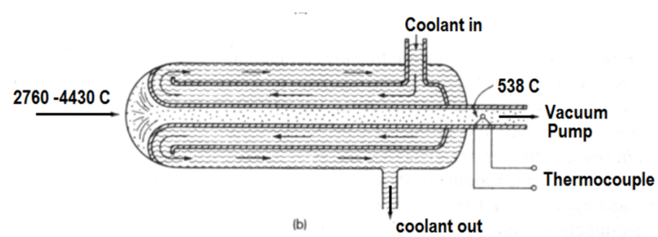

Hot gas is aspirated through a heat exchanger and cooling it to around 540°C.

The gas temperature is calculated from the knowledge of heat-transfer characteristics, flow rates , water inlet and out let temperatures as ell as from the gas outlet temeprature.

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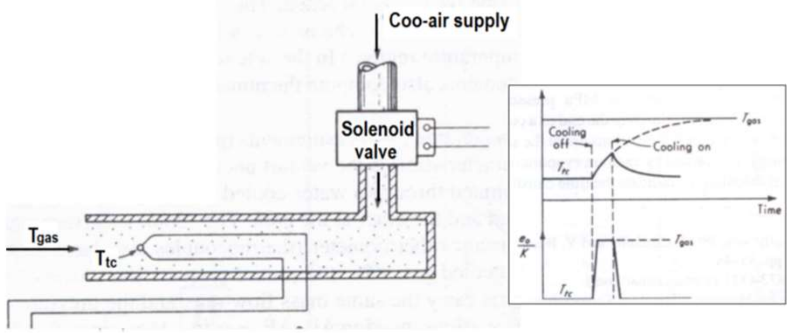
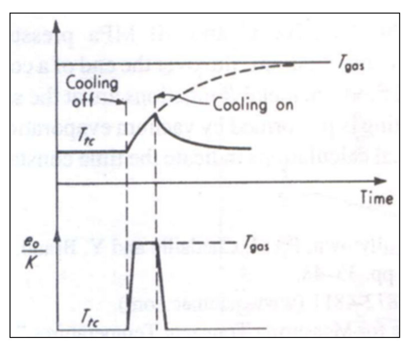
Pulsed-thermocouple technique



TC is generally K type (MP ~1400 C) to measure temperatures up to 4000C. The measuring junction is kept at a low temperature by a cooling flow. Then this flow is shut off by a solenoid valve, the thermocouple starts to heat up following the first order equation.

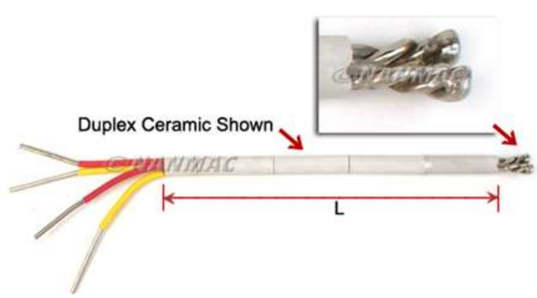


High temperature applications

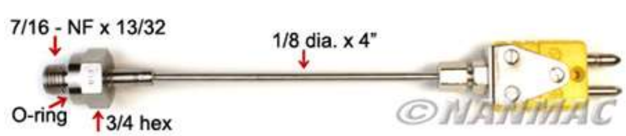
- TC is shielded in an enclosure.
- The measuring junction is kept at a low temperature by a cooling air flow.
- When this flow is shut off by a solenoid valve, the thermocouple starts to heat up, following the first order equation

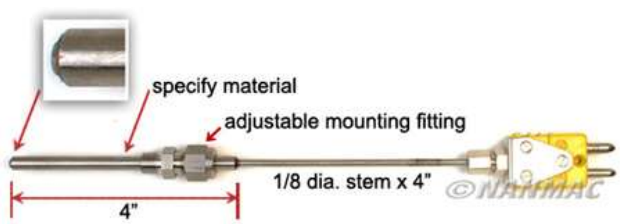
$$\tau \frac{dT_{tc}}{dt} + T_{tc} = T_{gas}$$

T_{gas} can be computed after the cooling is shut off if dT_{tc}/dt is known



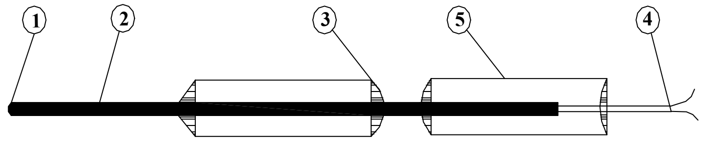
Heavy duty thermocouples



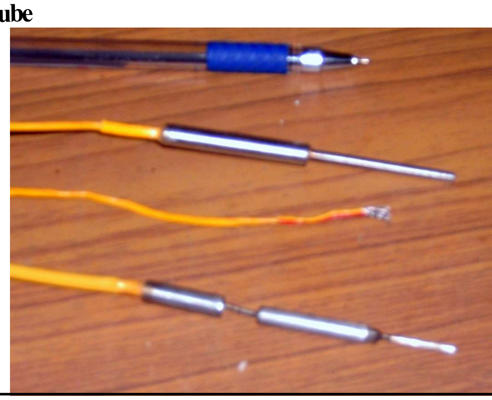


Pressure vessel

Metal sheathed K- type thermocouple



1. Grounded bead
2. Metal sheathed SS tube
3. MgO insulation
4. Thermocouple wires
5. SS-316 tube



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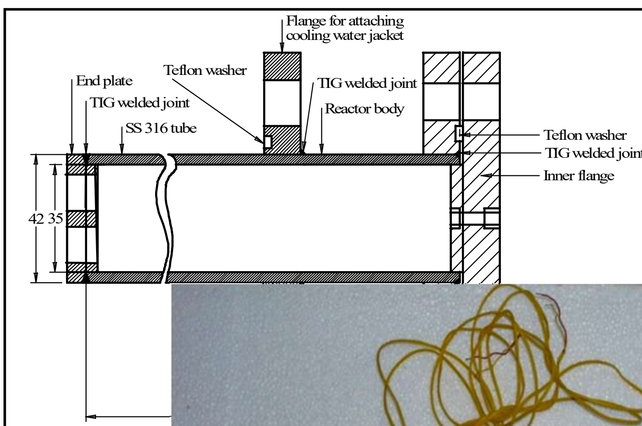
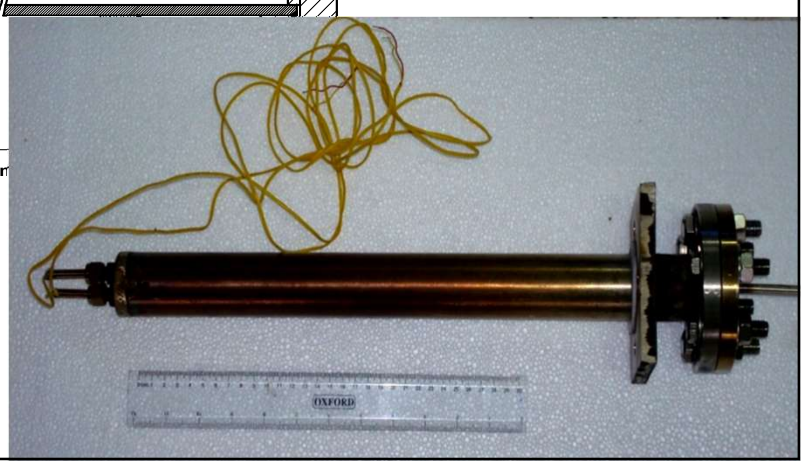
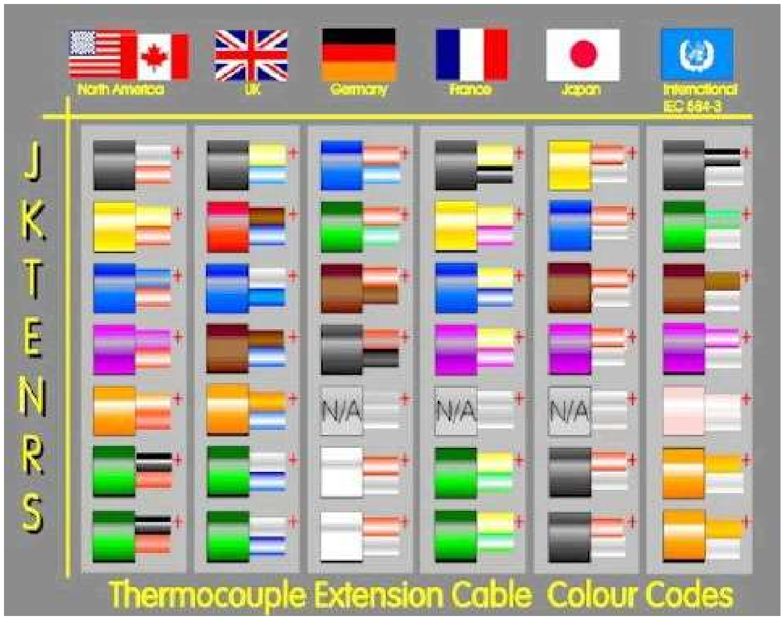




Colour codes of TCs Used in Different Countries



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Polynomial Coefficients for some standard TCs

	Type E	Type J	Type K	Type R	Type S	Type T
	Chromel(+) vs. Constantan(−)	Iron(+) vs. Constantan(−)	Chromel(+) vs. Nickel-5%(−) (Aluminum Silicon)	Platinum-13% Rhodium(+) vs. Platinum(−)	Platinum-10% Rhodium(+) vs. Platinum(−)	Copper(+) vs. Constantan(−)
	−100°C to 1000°C* ±0.5°C 9th Order	0°C to 760°C* ±0.1°C 5th Order	0°C to 1370°C* ±0.7°C 8th Order	0°C to 1000°C* ±0.5°C 8th Order	0°C to 1750°C* ±1°C 9th Order	−160°C to 400°C* ±0.5°C 7th Order
a_0	0.104967248	−0.048868252	0.226584602	0.263632917	0.927763167	0.100860910
a_1	17189.45282	19873.14503	24152.10900	179075.491	169526.5150	25727.94369
a_2	−282639.0850	−218614.5353	67233.4248	−48840341.37	−31568363.94	−767345.8295
a_3	12695339.5	11569199.78	2210340.682	1.90002E+10	8990730663	78025595.81
a_4	−448703084.6	−264917531.4	−860963914.9	−4.82704E+12	−1.63565E+12	−9247486589
a_5	1.10866E+10	2018441314	4.83506E+10	7.62091E+14	1.88027E+14	6.97688E+11
a_6	−1.76807E+11		−1.18452E+12	−7.20026E+16	−1.37241E+1	−2.66192E+13
a_7	1.71842E+12		1.38690E+13	3.71496E+18	6.17501E+17	3.94078E+14
a_8	−9.19278E+12		−6.33708E+13	−8.03104E+19	−1.56105E+19	
a_9	2.06132E+13				1.69535E+20	

$$T = a_0 + a_1x + a_2x^2 + ... + a_9x^9$$

T= Temperature, °C ; x= thermocouple voltage in volts

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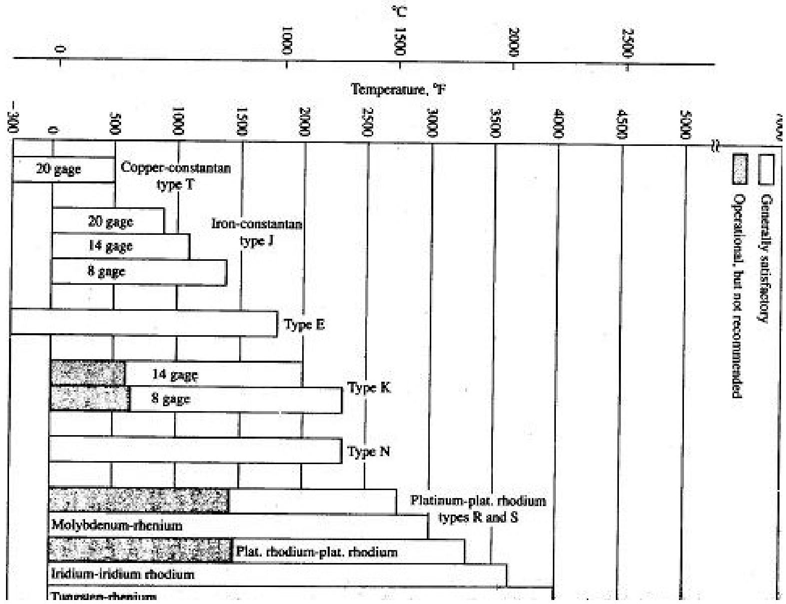
Source: H.P. Holman, Experimental Methods

Application range of different thermocouples



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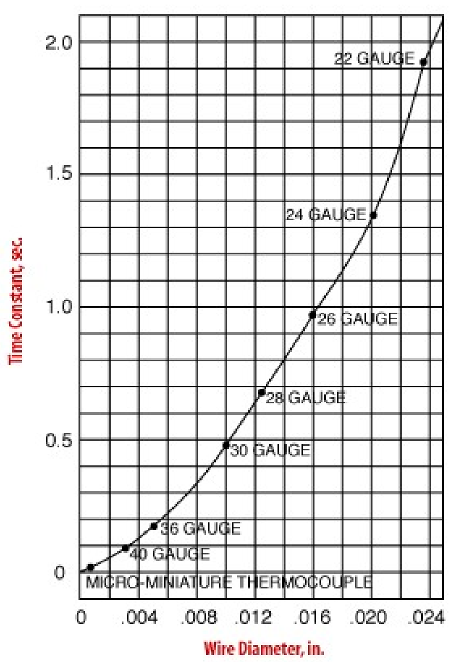
Source: H.P. Holman, Experimental Methods



TIME CONSTANT

$$\tau_t = \left(\frac{1}{hA_s}\right)(\rho V c)$$

Time Constant as a Function of wire Size for Exposed Wire Thermocouples in Air T=200°F.

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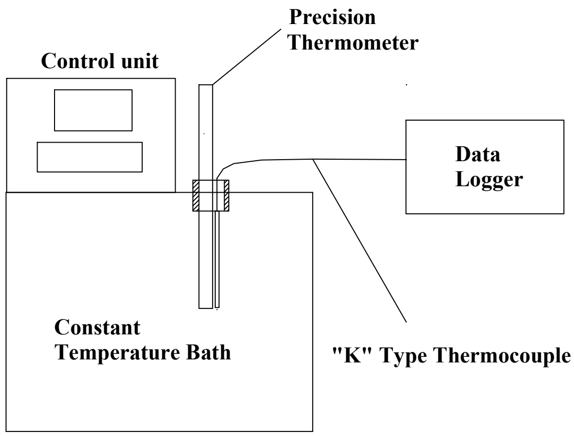

Schematic of calibration of the thermocouples

$$T_{act} = a + bT_d + cT_d^2$$

The regression coefficients are given by

a = 0.6341; b = 0.9994 T^{-1}; c = 3x 10-5 T^{-2}

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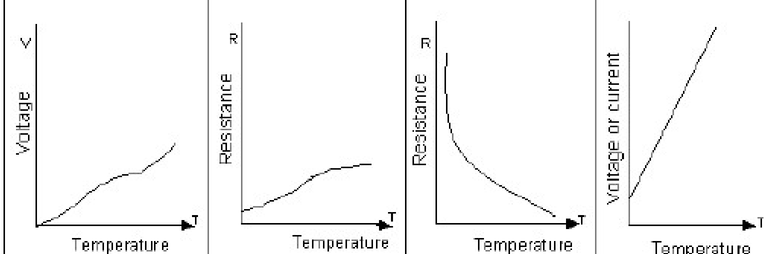

	Thermocouple	RTD	Thermistor	Integrated circuit sensor
Advantages	• Self powered • Simple • Rugged • Inexpensive • Wide variety • Wide temperature range	• Most stable • Most accurate • More linear than thermocouple	• High output • Fast • Two-wire ohms	• Most linear • Highest output • Inexpensive
Disadvantages	• Non linear • Low voltage • Reference required • Least stable • Least sensitive	• Expensive • Current source required • Small ΔR • Low absolute resistance • Self heating	• Non linear • Limited temperature range • Fragile • Current source required • Self heating	• T < 200 °C • Power supply required • Slow • Self heating • Limited configurations

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Liquid – Crystal Thermography

- Liquid crystals possess the mechanical properties of a liquid, but have the optical properties of a single crystal.
- Temperature changes affect the colour of the crystal, which makes them useful for temperature measurements.
- The range and resolution of liquid crystal thermometers is varied by varying the chemical composition.

  Ranges 0 to several hundreds

  Resolution of liquid crystal sensors ± 2°C (based on the range)
- Disposable liquid crystal thermometers have been developed for home and medical applications

  e.g. Cholesterol Liquid Crystals, Temperature paints.. Polyvinyl alcohol coating to avoid cracking of crystal

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Special Cases

Temperature measurement is Rapidly moving gas

When a temperature probe is placed in a stream of gas, the flow will be partially stopped by the probe. The local kinetic energy will be converted into heat, resulting in a temperature rise.

If the gas is brought to rest adiabatically, the resulting stagnation temperature (T_0) is given by;

$$T_0 = T_\infty + \frac{V^2}{2C_p}$$

In terms of Mach number

$$\frac{T_0}{T_\infty} = 1 + \frac{\gamma - 1}{2} M^2$$

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- In actual cases, the temperature measured by the probe will always higher than the free stream temperature and at the same time measured temperature will not be also equal to the stagnation temperature.
- The measure temperature is called as recovery temperature, which is strongly depends on the probe configuration. Hence, the recovery factor is defined as

$$r = \frac{T_r - T_\infty}{T_0 - T_\infty} = \frac{T_r - T_\infty}{V^2 / 2C_P}$$

$0.75 \le r \ge 0.99$ and r should found out for different flow conditions. It should be constant thro range of an instrument.

- The temperature measured by the probe is given by

$$T_r = T_\infty + \frac{rV^2}{2C_P}$$

$$T_r = T_0 - \frac{(1-r)V^2}{2C_P}$$

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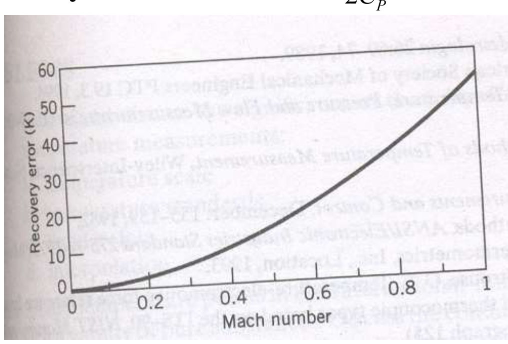
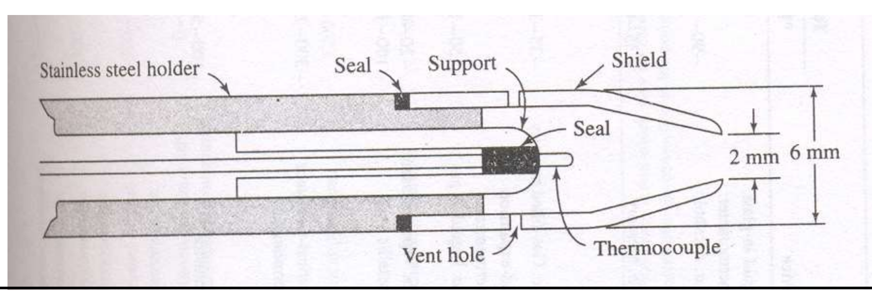
Recovery error $T_\infty - T_r = -\frac{rV^2}{2C_P}$

$$T_r = T_\infty + \frac{rV^2}{2C_P}$$





Radiation Methods

- All bodies above absolute zero emits radiation
- Black absorbs all incident radiation (ideal body)
- Thermal radiation is an electromagnetic waves emitted depends on the temperature.
- Temperature measurement is based on the thermal radiation (0.7 to 40 μ m; visible 0.3 to 0.72 and infrared 0.72 to 1000 μ m)
- Its Non contact type, applied for high temperature body / surface.
- Types: Radiation Pyrometer or Radiation Thermometer, Optical Pyrometers and IR Thermometer

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1. Plank Distribution Law (spectral distribution of blackbody emission)

$$E_{b\lambda} = \frac{C_1 \lambda^{-5}}{e^{c_2/\lambda T} - 1} \quad W / cm^2 . \mu m$$

λ = Wave Length, μm

C1 = 3.743 x 104^4 W.$\mu m^4/cm^2$; C2 = 1.4387x 10^4μm K

2. Wien Displacement Law:

Gives the wave length of peak intensity

$$C = 2897.8 \mu m K = \lambda_{\max} T$$

3. Stefan – Boltzmann Law

$$E_b = \sigma T^4$$

σ = Stefan boltzmann constant = 5.67 x 10^{-8} $W/m^2.K^{-4}$

Basics of an Optical Pyrometer. By observing the colour of the radiation, unknown temperature is measured

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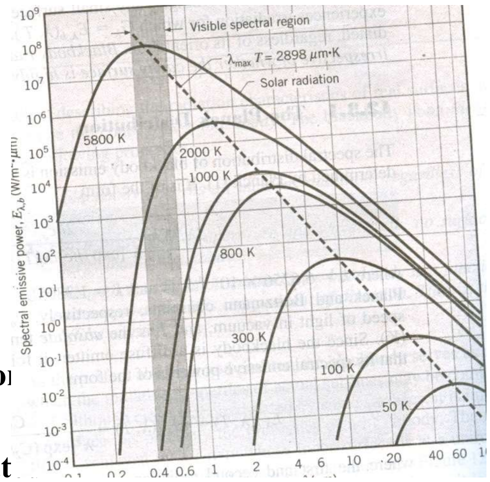
Infrared Thermometers

- Non – contact type; are sensitive to radiation in the IR range.
- Range from 0.7 to 20 mico meters (Non visible region)
- Not sensitive enough to measure beyond this range since intensity is very small.



- Based on wiens displacement Law: peak intensity of radiatio occur at infrared wavelengths
- Receives the heat energy radiat from objects and converts into electrical output.

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Radiation Thermometers/Pyrometers

- Radiation from the measured body is focused on some radiation detector (single or array) which produces an electric signal.
- It can be a thermal detector (thermistor or RTD) or Photon detector (photovoltaic material)
- Thermal detectors are blackened elements designed to absorb a maximum of incoming radiation at all wavelengths.
- Temperature rise until an equilibrium is reached with heat losses to the surroundings
- Measure this temperature with resistance thermometer.

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Radiation Thermometers (Bolometer)

- Incoming radiation heats the measuring junction until conduction, convection and radiation losses just balance the heat input.
- Heat loss = radiant heat input

$$\sigma T_1^4 = K(T_2 - T_3)$$

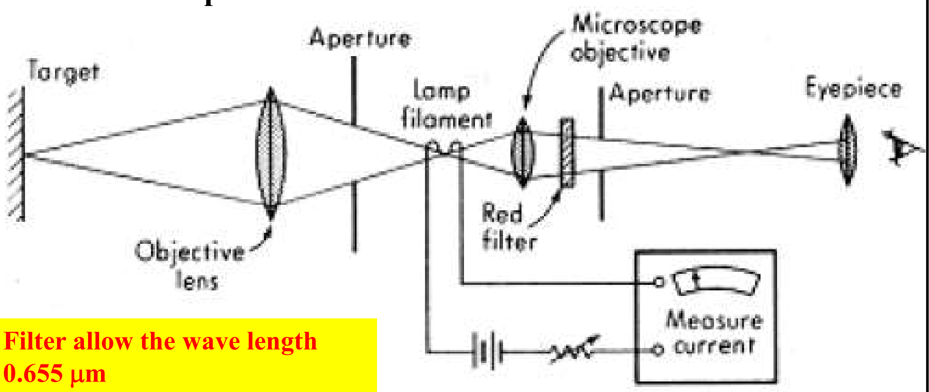
Thermopiles are used to measure T_2-T_3. Voltage output from thermopile is proportional to the unknown temperature of the source T_1.

Generally thermopiles of 20 to 30 junctions are used.

- Thermistors are made in the form of thin films or flakes.
- Even without radiation, a small random voltage due to various electrical noise in the device.
- Noise equivalent power : The amount of incoming radiation required to nullify the effect of electrical noise
- Nickel –film Bolometer. Area 35 mm^2, Resistance 100 ohm, sensitivity of 0.4V/W and τ = 0.004 s
- Thermistor bolometer of 0.5 mm^2, 3 M ohm resistance, a time constant of 0.004 to 0.03 s.

Optical Pyrometers (Brightness Radiation Thermometer)

- **Temperature ranges of 700 to 3000°C. An image of the heat source is superimposed on a heated tungsten filament.**
- **At a given λ, the radiation intensity(brightness) varies with temperature.**



Filter allow the wave length 0.655 μm

- **Lamp current is adjusted until the filament disappears, in the superimposed source image.**
- **If the current through the filament is known, the brightness temperature of the filament is found.**
- **Very stable instrument, calibration is easy.**
- **Used all types of furnaces**
- **Typical error**
- **± 3 °C at 1000 °C ; ± 6 °C at 2000 °C**

  ± 40 °C at 4000 °C
- **If the target is perfect black body, ε =1, error is zero.**

$$\frac{dT_t}{T_t} = \frac{\lambda T_t}{C_2}\frac{d\varepsilon_\lambda}{\varepsilon_\lambda}$$

10% error in ε results to only 0.5 % error in T

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