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MetForTC

FSB — Sveučilište u Zagrebu, Fakultet strojarstva i brodogradnje

EMPIR JRP 18RPT03 MetForTC

WORKSHOP
Temperature measurement by thermocouples

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Zagreb, Croatia, 27 February, 2020

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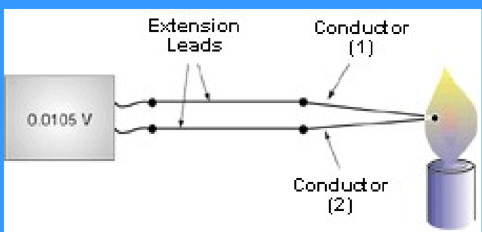
Thermocouples

- Thermocouples are the most common sensors in industrial use.
- They have a long history, the original paper on thermoelectricity by Seebeck being published in 1822.
- They consist of two dissimilar metallic conductors joined at the point of measurement.
- When the conductors are heated a voltage is generated in the circuit, and this can be used to determine the temperature.



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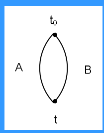
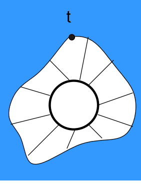
Properties



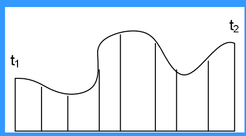
$$e_{AB} = f(t)$$

- Thermovoltage is a function of temperature



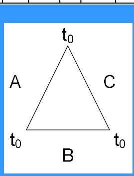
$$e = \int_t^t de = \int_t^t df(t) = f(t) - f(t) = 0$$

- There can be no thermovoltage in closed homogeneous conductor



$$e = \int_{t_1}^{t_2} de = \int_{t_1}^{t_2} df(t) = f(t_2) - f(t_1)$$

- The thermovoltage in an open homogeneous conductor depends only on the temperature of its ends



$$e_{AB}(t_0) + e_{BC}(t_0) + e_{CA}(t_0) = 0$$

- The thermovoltage in a homogeneous triangle with the same temperature at its junctions must equal zero.

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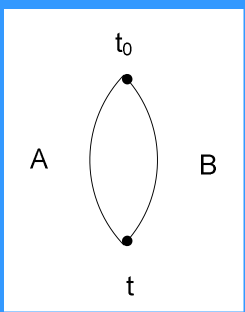
Equation of Thermocouple



$$\mathrm{E}_{AB}(t,t_0) = e_{AB}(t) + e_{BA}(t_0)$$

$$e_{BA}(t_0) = -e_{AB}(t_0)$$

$$\mathrm{E}_{AB}(t,t_0) = e_{AB}(t) - e_{AB}(t_0)$$

$$\mathrm{E} = f(materijala, t, t_0, ...)$$

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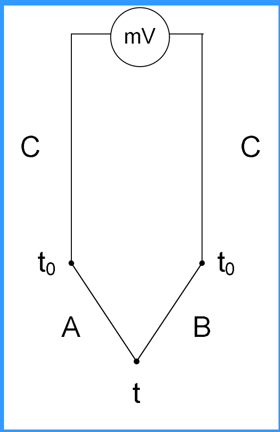
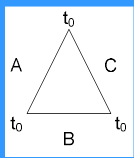
Connection to the Voltmeter



$$E = e_{AB}(t) + e_{BC}(t_0) + e_{CA}(t_0);$$
$$\rightarrow e_{CA}(t_0) = -e_{AB}(t_0) - e_{BC}(t_0)$$
$$E = e_{AB}(t) + e_{BC}(t_0) - e_{AB}(t_0) - e_{BC}(t_0)$$
$$E = e_{AB}(t) - e_{AB}(t_0) = E_{AB}(t, t_0)$$



$$e_{AB}(t_0) + e_{BC}(t_0) + e_{CA}(t_0) = 0$$

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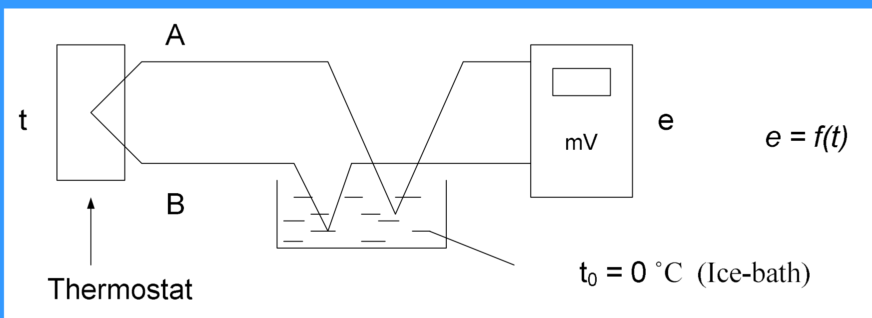
Generation of the e=f(T) Tables



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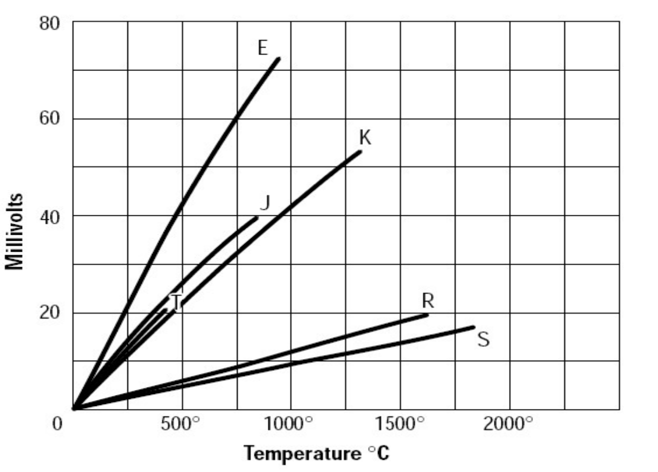
Basic Types of Thermocouples



Thermal voltage is a function of temperature, E=E(t)

This function is not linear!

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Thermocouple Classes and Tolerances

Standardized tolerances and approximate accuracies acievable with calibration

Type	Range	Tolerance (from standard polynomial)		Calibration
T	-250 / +400 °C	± 1 K	0 / 100 °C	0,1 K
		± 1 %	100 / 400 °C	0,2 K
J	-200 / +800 °C	± 3 K	0 / 300 °C	0,5 K
		± 1 %	300 / 850 °C	1 K
K	-200 / +1100 °C	± 3 K	0 / 400 °C	0,5 K
		± 0,75 %	100 / 400 °C	1 K
S	0 / +1400 °C	± 1 K	0 / 1100 °C	0,5 K
		± 2 K	1100 / 1400 °C	1-2 K

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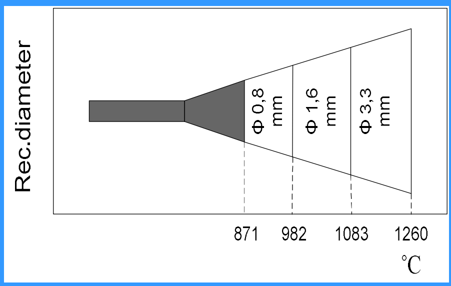
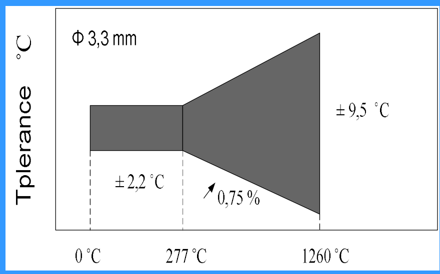
Diameter, Temperature Range and Tolerance





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Thermocouple Classes and Tolerances

IEC Tolerance Class EN 60584-2; JIS C 1602

IEC Code		Class 1	Class 2	Class 3†
J	Temp Range Tolerance Value Temp. Range Tolerance Value	-40 to 375°C ±1.5°C 375 to 750°C ±0.4% Reading	-40 to 333°C ±2.5°C 333 to 750°C ±0.75% Reading	Not Established
K N	Temp Range Tolerance Value Temp. Range Tolerance Value	-40 to 375°C ±1.5°C 375 to 1000°C ±0.4%	-40 to 333°C ±2.5°C 333 to 1200°C ±0.75% Reading	-167 to 40°C ±2.5°C -200 to -167°C ±1.5% Reading
T	Temp Range Tolerance Value Temp. Range Tolerance Value	-40 to 125°C ±0.5°C 125 to 350°C ±0.4% Reading	-40 to 133°C ±1°C 133 to 350°C ±0.75% Reading	-67 to 40°C ±1°C -200 to -67°C ±1.5% Reading
E	Temp Range Tolerance Value Temp. Range Tolerance Value	-40 to 375°C ±1.5°C 375 to 800°C ±0.4% Reading	-40 to 333°C ±2.5°C 333 to 900°C ±0.75% Reading	-167 to 40°C ±2.5°C -200 to -167°C ±1.5% Reading
R S	Temp Range Tolerance Value Temp. Range Tolerance Value	0 to 1100°C ±1°C 1100 to 1600°C ±[1 + 0.3% x (Rdg-1100)]°C	0 to 600°C ±1.5°C 600 to 1600°C ±0.25% Reading	Not Established
B	Temp Range Tolerance Value Temp. Range Tolerance Value	Not Established	600 to 1700°C ±0.25% Reading	600 to 800°C +4°C 800 to 1700°C ±0.5% Reading

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Thermocouple Reference Function and Coefficients

Type J Thermocouples - coefficients, c_i, of reference equations giving the thermoelectric voltage, E, as a function of temperature t_{90}, for the indicated temperature ranges. The equations are of the form:

$$E = \sum_{i=0}^{n} c_i (t_{90})^i$$

where E is in microvolts and t_{90} is in degrees Celsius.

Temperature Range:	-210 to 760°C	760 to 1,200°C
c_0 =	0.000 000 000 0	2.964 562 568 1 x 10^5
c_1 =	5.038 118 781 5 x10^1	-1.497 612 778 6 x 10^3
c_2 =	3.047 583 693 0 x 10^{-2}	3.178 710 392 4
c_3 =	-8.568 106 572 0 x 10^{-5}	-3.184 768 670 1 x 10^{-3}
c_4 =	1.322 819 529 5 x 10^{-7}	1.572 081 900 4 x 10^{-6}
c_5 =	-1.705 295 833 7 x 10^{-10}	-3.069 136 905 6 x 10^{-10}
c_6 =	2.094 809 069 7 x 10^{-13}	
c_7 =	-1.253 839 533 6 x 10^{-16}	
c_8 =	1.563 172 569 7 x 10^{-20}	

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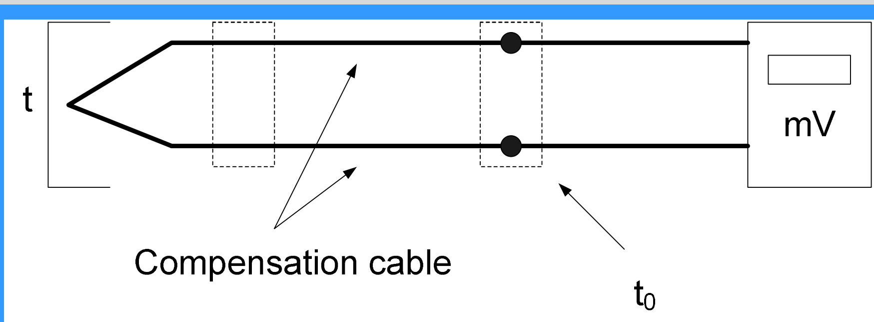
Compensation cable



If, for practical reasons, the length of a thermocouple has to be increased this shall be made by the use of the correct extension or compensating cable. Extension cable consists of conductors made of nominally the same materials as the thermocouple conductors while compensating cable is made from a different pair of alloys. The cables are manufactured to match the emf/temperature characteristic of the thermocouple itself but over a restricted temperature range, no wider than -40 °C to +200 °C. Manufacturing tolerances are specified in EN IEC 60584-3.

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Case When $t_0 \neq 0$ °C (almost always in measurement)

Let the reference junction temperature $t_0' > t_0$; The difference is then:

$$E_{AB}(t,t_0) - E_{AB}(t,t_0') = (iz(4)) \rightarrow = e_{AB}(t) - e_{AB}(t_0) - e_{AB}(t) + e_{AB}(t_0') =$$

$$= e_{AB}(t_0') - e_{AB}(t_0) = E_{AB}(t_0',t_0) \Rightarrow$$

$$\Rightarrow E_{AB}(t,t_0) = E_{AB}(t,t_0') + E_{AB}(t_0',t_0)$$

For this E we have reference tables

This is E we are measuring

This E we must add on the basis of t'

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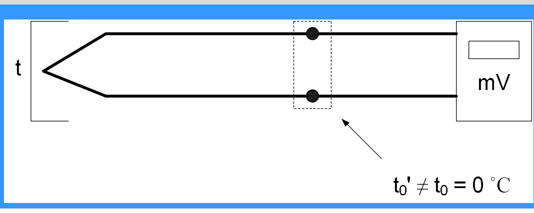
Case A $t_0 \neq 0$ °C (Tables $t = f[E(t,t0 = 0)]$ are not valid



Case A1:

1. We measure $E(t,t_0')$
2. We measure t_0'
3. From tables we convert : $t' = f[E(t,t_0')]$
4. We add $t = t' + t_0'$

We are in error because $t(e_t + e_{t_0'}) \neq t(e_t) + t(e_{t_0'})$

Error is small for $t_0' \approx t_0$

Case A2:

1. We measure $E(t,t_0') = e'$
2. We measure t_0'
3. From tables we find: $t' = f[E,t_0',t_0)] = e_0'$
4. We add $e = e' + e_0'$
5. From tables we find $t = f(e)$ (this is fully correct)

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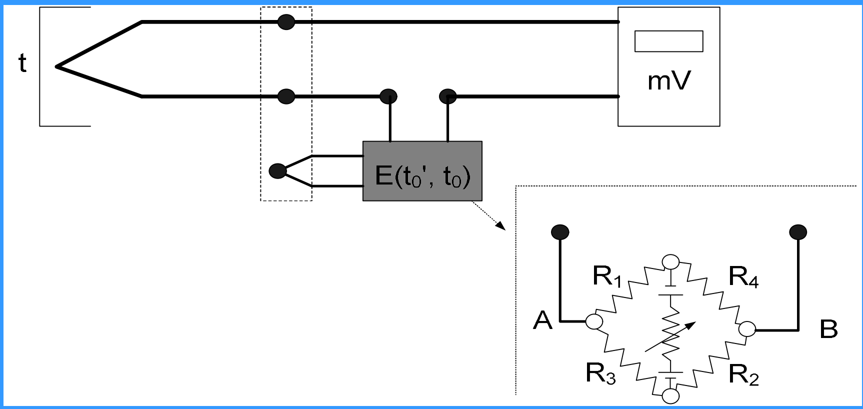
Case A3 - Automatic Compensation of Reference temperature



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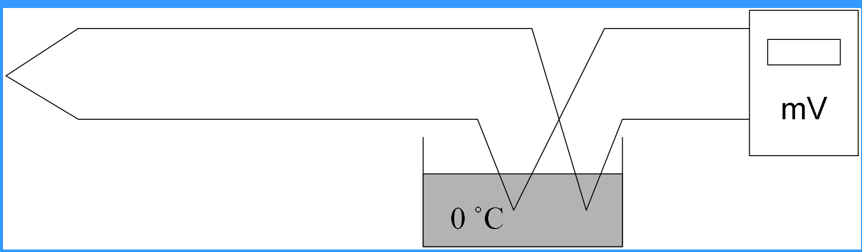
Case B1- We make sure that t_0 = 0 ˚C With Ice-Bath



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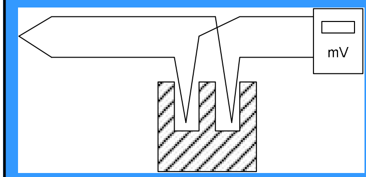
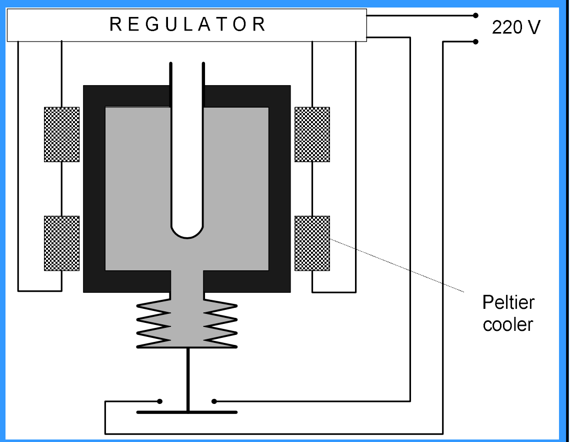
Case B1- We make sure that $t_0 = 0\ ^\circ C$ With Ice-Point Cell





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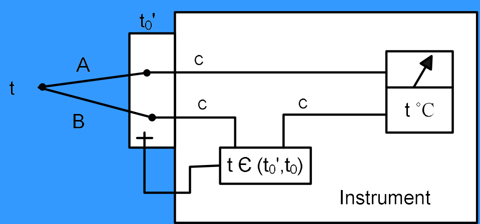
We have Automatic Compensation of Reference Temperature



$$E = e_{AB}(t) + e_{BC}(t_0') + e_{AB}(t_0') - e_{AB}(t_0) + e_{CA}(t_0');$$

$$e_{AB}(t_0') + e_{BC}(t_0') + e_{CA}(t_0') = 0 \Rightarrow$$

$$\Rightarrow e_{BC}(t_0') + e_{CA}(t_0') = -e_{AB}(t_0')$$

$$E = e_{AB}(t) - e_{AB}(t_0') + e_{AB}(t_0') - e_{AB}(t_0)$$

$$E = e_{AB}(t) - e_{AB}(t_0) = E_{AB}(t, t_0)$$

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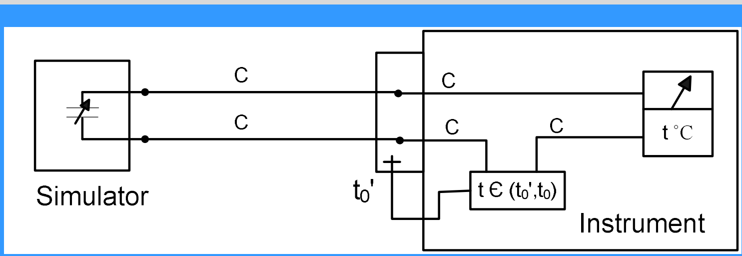
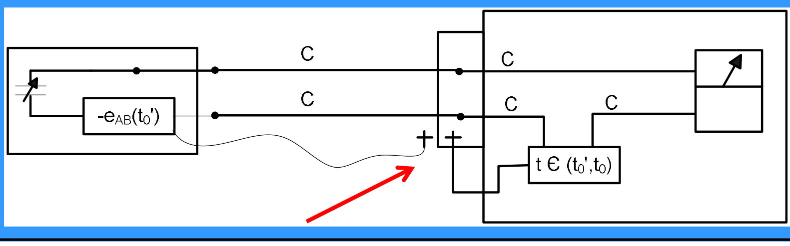
Calibration – Simulation With Copper Cables



$$\mathrm{E} = e_{AB}(t) + e_{AB}(t_0') - e_{AB}(t_0)$$

$$\mathrm{E} = e_{AB}(t) - e_{AB}(t_0) + e_{AB}(t_0') = \mathrm{E}_{AB}(t, t_0) + e_{AB}(t_0')$$



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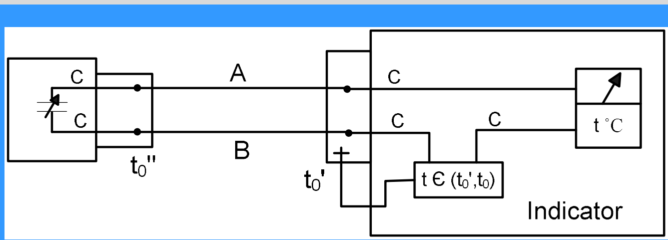
Calibration – Simulation With Thermocouple Cables



$$\mathrm{E} = e_{AB}(t) + e_{CB}(t_0'') + e_{BC}(t_0') + e_{AB}(t_0') - e_{AB}(t_0) + e_{CA}(t_0') + e_{AC}(t_0'');$$

$$e_{BC}(t_0') + e_{CA}(t_0') = -e_{AB}(t_0')$$

$$e_{AC}(t_0'') + e_{CB}(t_0'') + e_{BA}(t_0'') = 0$$

$$-e_{BA}(t_0'') = e_{AC}(t_0'') + e_{CB}(t_0'')$$

$$e_{AB}(t_0'') = -e_{BA}(t_0'')$$

$$\mathrm{E} = e_{AB}(t) + e_{AB}(t_0'') - e_{AB}(t_0') + e_{AB}(t_0') - e_{AB}(t_0)$$

$$\mathrm{E} = e_{AB}(t) - e_{AB}(t_0) + e_{AB}(t_0'') = \mathrm{E}_{AB}(t, t_0) + e_{AB}(t_0'')$$

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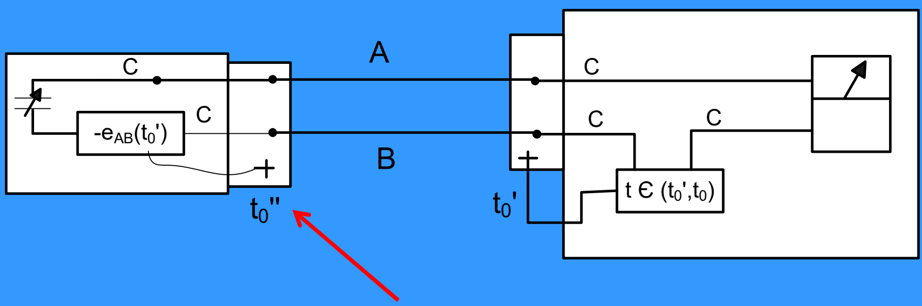
Calibration – Simulation With Thermocouple Cables



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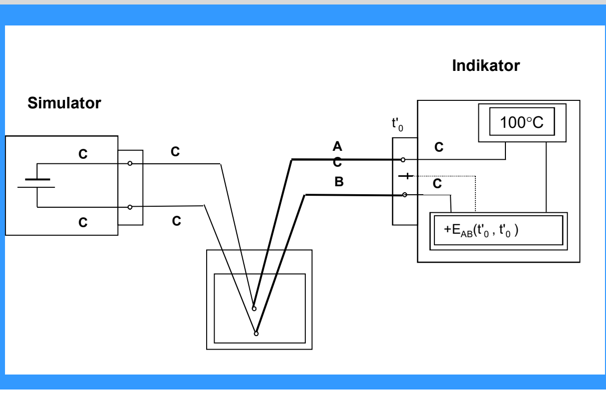
Calibration – Simulation With Ice Baths and Thermocouple Wire



$$E = e_{AB}(t=100°C) + e_{CB}(0°C) + e_{BC}(t_0') + e_{AB}(t_0') - e_{AB}(t_0=0°C) + e_{CA}(t_0') + e_{AC}(0°C)$$

$$e_{BC}(t_0') + e_{AB}(t_0') + e_{CA}(t_0') = 0 \Rightarrow$$

$$E = e_{AB}(t=100°C) + e_{CB}(0°C) - e_{AB}(t_0=0°C) + e_{AC}(0°C)$$

$$-e_{AB}(t_0=0°C) = e_{BA}(t_0=0°C) \Rightarrow$$

$$e_{CB}(0°C) + e_{BA}(t_0=0°C) + e_{AC}(0°C) = 0 \Rightarrow$$

$$E = e_{AB}(t=100°C)$$

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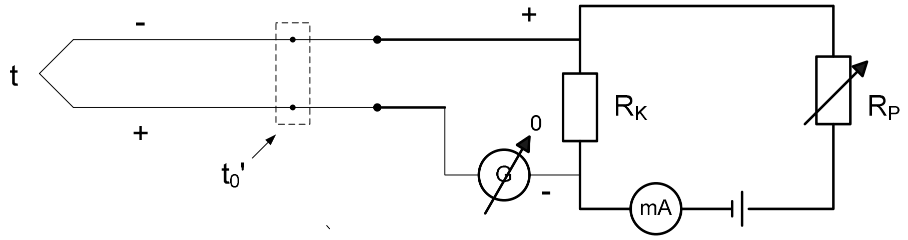
Measurement of Thermovoltage
Case When Lead Resistance Can be Neglected
(Compensation method, Lindeck-Rothe bridge)



$$E = I \cdot R_K$$

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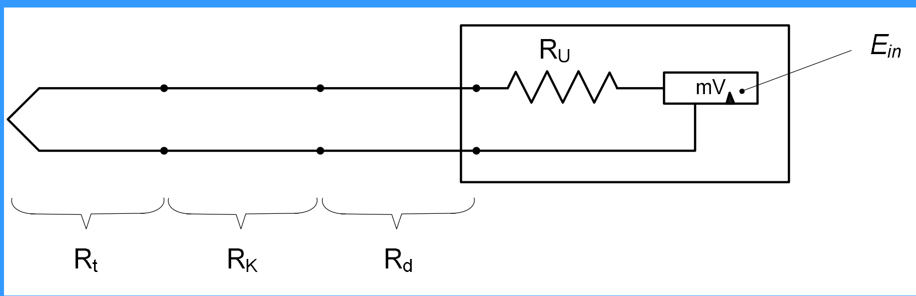
Measurement of Thermovoltage
Case When Lead Resistance Can Not be Neglected



$$E = E_{in} \frac{R_t + R_k + R_d + R_u}{R_u} = kE_{in}$$

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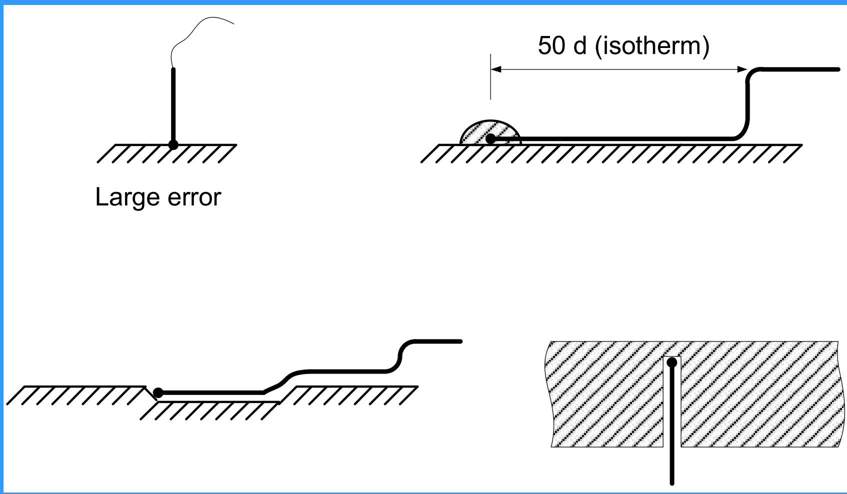
Measurement of Surface Temperature With Thermocouples

For $T_{wall} > T_{fluid}$ measured temperature is always less than T_{wall} !



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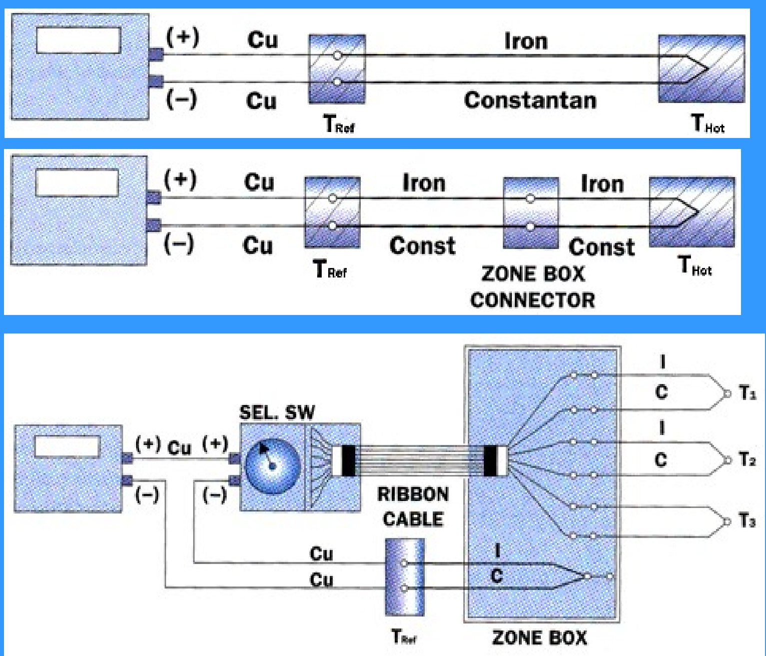

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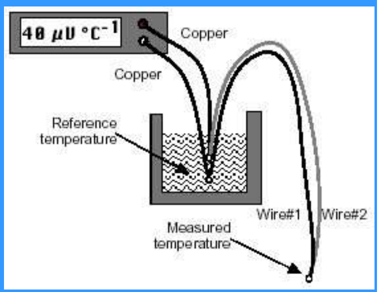
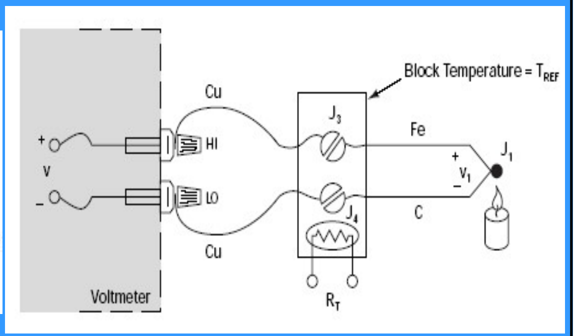
Thermocouple – Calibration Lab and Industial Principle





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Thank you for your attention!

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