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Chapter 3: Temperature Sensors and Thermal Actuators

1. **Temperature scales and units**
2. **Temperature sensors types**
   - *I. Thermoresistive sensors and actuators:*
     - a) Resistance Temperature Detectors (RTD)
     - b) Silicon resistive sensors
     - c) Thermistors
   - *II. Thermoelectric sensors:*
     - a) Thermocouples
     - b) Semiconductor thermocouples
     - c) Thermopiles
     - d) Thermoelectric generators (Peltier Cell)
   - *III. p–n junction temperature sensors*
   - *IV. Other temperature sensors*
     - a) Optical and acoustical sensors
     - b) Thermomechanical sensors and actuators

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A bit of history

- Temperature sensor is the *oldest sensors* (except magnetic compass)
- History of temperature measurements and thermometers:

- **1600** – Introduction of thermometers (water expansion, mercury)
- **1650** - first attempts at temperature scales (Boyle)
- **1700** –Temperature scales (Magelotti, Renaldini, Newton) – didn't catch
- **1708** - Fahrenheit scale (180 div between freezing and boiling points of water)
- **1742** - Celsius scale (100 div between freezing and boiling points of water)
- **1848** - Kelvin scale (based on Carnot's thermodynamic work)
- **1927** - IPTS - International Practical Temperature Scale
- **1821** - Seebeck effect (Thomas Johann Seebeck)
  - ***1826*** - *first temperature sensor* - *a thermocouple* - based on the Seebeck effect (Antoine Cesar Becquerel)
- **1834** - Peltier effect (Charles Athanase Peltier).
  - *First Peltier cell built in 1960's (for cooling and heating for space applications)*
- **1821** - discovery of temperature dependence of conductivity (Humphrey Davey)
  - *1871 - William Siemens builds the first resistive sensor made of platinum*

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Temperature scales

Temperature scales:

- **Centigrade (Celsius (ºC)) scale:** 0ºC at freezing point of water (triple point of water is reference), 100ºC at boiling point of water
- **Standard scale (K):** Kelvin scale (absolute zero is reference),
  - Absolute zero at -273.15 ºC
  - Freezing point of water at 273.15 K,
  - Boiling point of water at 373.15 K
- **Fahrenheit scale (ºF):**
  - Freezing point of water at 32 ºF
  - Boiling point of water at 212 ºF
  - Absolute zero at -459.67 ºF
- **Conversion between scales:**

$$\begin{aligned}
\text{From } {}^\circ\text{C to K: } N\,[{}^\circ\text{C}] &= (N + 273.15)\,[\text{K}] \\
\text{From } {}^\circ\text{C to } {}^\circ\text{F: } P\,[{}^\circ\text{C}] &= (P \times 1.8 + 32)\,[{}^\circ\text{F}] \\
\text{From K to } {}^\circ\text{C: } M\,[\text{K}] &= (M - 273.15)\,[{}^\circ\text{C}] \\
\text{From } {}^\circ\text{F to } {}^\circ\text{C: } Q\,[{}^\circ\text{F}] &= (Q - 32)/1.8\,[{}^\circ\text{C}] \\
\text{From K to } {}^\circ\text{F: } S\,[\text{K}] &= (S - 273.15) \times 1.8 + 32\,[{}^\circ\text{F}] \\
\text{From } {}^\circ\text{F to K: } U\,[{}^\circ\text{F}] &= (U - 32)/1.8 + 273.15\,[\text{K}]
\end{aligned}$$

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Heat and Heat Capacity

- **Heat** is a form of energy – units of joule [J]
  - 1 j = 1 W.s, 1 kWh = 3.6 MJ, 1 cal = 0.239 j
  - (the kWh and the calorie (cal) are not SI units)
- **Thermal conductivity (k or λ):** the ability of materials to conduct heat. Denoted as k or λ, units: (W/[m.K])
- **Heat capacity (C):** Amount of heat (energy) necessary to change the temperature of a substance by a given amount. units: (J/K)
- **Molar heat capacity:** energy necessary to change the temperature of one mole of substance. Units: (J/[mol.K])
- **Specific heat capacity:** energy necessary to change the temperature of *1 kg* of substance by *1 K*. Units: (J/[kg.K])
- **Volumetric heat capacity:** energy necessary to change the temperature of $1\ m^3$ of substance (gas) by *1 K*. Units: (J/[m^3.K])
- Often specific heat capacity is given in units of (J/[g.K]) and that of volumetric heat capacity in units of (J/[cm^3.K])

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Temperature sensors - general

- Temperature sensors can be deceptively simple, for example:
  - **Thermocouples**: any two dissimilar materials, welded together at one end and connected to a micro-voltmeter
  - **Peltier cell:** any thermocouple connected to a dc source (polarity defines heating or cooling)
  - **Resistive sensor:** a length of a conductor connected to an ohmmeter
- Some temperature sensors can act as *actuators* as well
- Can be used to measure *other quantities* that can affect temperature (electromagnetic radiation, air speed, flow, etc.)
- Many newer sensors are *semiconductor based*

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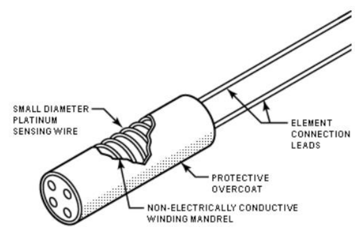
Temperature sensors - types

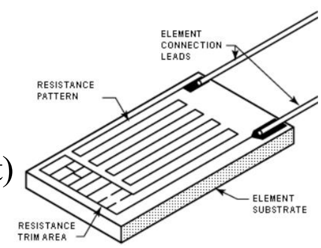
- **Thermoresistive sensors and actuators:**
  - Conductor based sensors and actuators (RTDs)
  - Semiconductor based sensors - thermistors
- **Thermoelectric sensors:**
  - Thermocouples and thermopiles
  - Peltier cells (used as actuators but can be used as sensors)
- **Semiconductor junction sensors**
- **Others**
  - Based on secondary effects (speed of sound, phase of light)
  - Indirect sensing (infrared thermometers – in chapter 4)
  - Expansion of metals, bimetals (actuators or sensors-actuators)

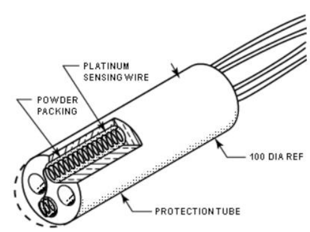
Thermoresistive sensors

Two basic types:

- Resistive Temperature Detector (RTD)
  - ➢ Metal wire
  - ➢ Thin film
  - ➢ Coiled Element RTD
  - ➢ Silicon based
- Thermistors (Thermal Resistor)
  - ➢ Mainly NTC (Negative Temperature Coefficient)
  - ➢ PTC (Positive Temperature Coefficient)







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Resistance temperature detectors

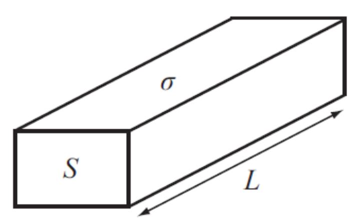
- Early sensors of this type were made of an appropriate metal such as ***platinum***, ***nickel***, or ***copper***, depending on the *application*, *temperature range*, and often the *cost*.
- All RTDs are based on the change in ***resistance***
- The resistance of a conductor of length L with constant cross-sectional area S and conductivity σ is:

$$R = \frac{L}{\sigma S}\,[\Omega]$$

- Conductivity is the measure of the ease at which an electric charge or heat can pass through a material and is temperature dependent.

$$\sigma = \frac{\sigma_0}{1 + \alpha[T - T_0]}\,[\frac{S}{m}]$$

Where $\boldsymbol{\alpha}$ the temperature ***coefficient of resistance (TCR)***$[C^{-1}]$ of material, σ_0 is conductivity of conductor at reference temperature (T_0), usually 20°C



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Resistance temperature detectors

- Resistance of the conductor as a function of temperature:

$$R = \frac{L}{\sigma_0 S}(1 + \alpha[T - T_0])[\Omega]$$

Or

$$R = R_0(1 + \alpha[T - T_0])[\Omega]$$

Where R_0, is the resistance at the reference temperature, T_0 (base resistance)
T and T_0 can be in degrees Celsius or kelvin (same division)

- **Example:** Copper: $\sigma_0 = 5.8 \times 10^7 s/m$, $\alpha = 0.0039/°\text{C}$ at $T_0 = 20°\text{C}$, Wire of cross-sectional area: $S = 0.1mm^2$, and length $L = 1m$
- Base resistance at 20°C :

$$R_0 = \frac{L}{\sigma_0 S} = \frac{1}{5.8 \times 10^7 \times 0.1 \times 10^{-6}} = 0.017\Omega$$

- Change in resistance of:

$$\Delta R = R_0 \alpha \Delta T = 0.017 \times 0.0039 \times 1 = 6.63 \times 10^{-5}\Omega$$

Change of **0.38%** per °C

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Resistance temperature detectors

Conclusions from this example:

- For the sensor to be practical the conductor must be ***long*** and ***thin*** and/or ***conductivity*** must be ***<u>low</u>*** with ***<u>large</u> temperature coefficient*** to have easier signal processing.

Material	Conductivity[1] σ [S/m]	Temperature coefficient[3] of resistance [per °C]
Copper (Cu)	5.8×10^7	0.0039
Carbon (C)	3.0×10^5	−0.0005
Constantan (60% Cu, 40% Ni)	2.0×10^6	0.00001
Chromium (Cr)	5.6×10^6	0.0059
Germanium (Ge)	2.2	−0.05
Gold (Au)	4.1×10^7	0.0034
Iron (Fe)	1.0×10^7	0.0065
Mercury (Hg)	1.0×10^6	0.00089
Nichrome (NiCr)	1.0×10^6	0.0004
Nickel (Ni)	1.15×10^7	0.00672
Platinum (Pl)[2]	9.4×10^6	0.003926 (at 0 °C)
Silicon (Si) (pure)	4.35×10^{-6}	−0.07
Silver (Ag)	6.1×10^7	0.0016
Titanium (Ti)	1.8×10^6	0.042
Tungsten (W)	1.8×10^7	0.0056
Zinc (Zn)	1.76×10^7	0.0059
Aluminum (Al)	3.6×10^7	0.0043

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Resistance temperature detectors

- RTD range temperature is usually between $-200°C$ to $600°C$
- Transfer function can be obtained two ways

1) the manufacturers follow the existing standards that specify the coefficient α that a sensor uses (part of the sensor's specifications).
   - Standard EN 60751, dealing with platinum RTDs, specifies $\alpha = 0.00385$ (this is sometimes called the "European curve")
   - Other values are 0.003926 ("American curve"), 0.003916, and 0.003902, among others, and relate to grades of platinum

- This allows us to establish an <u>*approximate*</u> transfer function as follows:

$$R = R(0)(1 + \alpha T)[\Omega]$$

Where R(0) is the resistance at $0°C$ (<u>*nominal resistance*</u>)

- This is an *approximate* value because α is itself ***temperature dependent***
- However, for *small sensing spans* close to the nominal temperature, the temperature curve is nearly linear this transfer function is ***sufficiently accurate***.

RTD Temperature vs. Resistance Table

For European Curve, Alpha = 0.00385, ITS-90 — 1° Celsius Increments

°C	Ohms	Diff.	°C	Ohms	Diff.	°C	Ohms	Diff.	°C	Ohms	Diff.	°C	Ohms	Diff.	°C	Ohms	Diff.
-200	18.52		-140	43.88	0.42	-80	68.33	0.41	-20	92.16	0.39	± 0	100.00	0.39	+60	123.24	0.38
199	18.96	0.44	139	44.29	0.41	79	68.73	0.40	19	92.55	0.39	+ 1	100.39	0.39	61	123.62	0.38
198	19.39	0.43	138	44.71	0.42	78	69.13	0.40	18	92.95	0.40	2	100.78	0.39	62	124.01	0.39
197	19.82	0.43	137	45.12	0.41	77	69.53	0.40	17	93.34	0.39	3	101.17	0.39	63	124.39	0.38
196	20.25	0.43	136	45.53	0.41	76	69.93	0.40	16	93.73	0.39	4	101.56	0.39	64	124.77	0.38
195	20.68	0.43	135	45.95	0.42	75	70.33	0.40	15	94.12	0.39	5	101.95	0.39	65	125.17	0.40
194	21.11	0.43	134	46.35	0.40	74	70.73	0.40	14	94.52	0.40	6	102.34	0.39	66	125.55	0.38
193	21.54	0.43	133	46.76	0.41	73	71.13	0.40	13	94.91	0.39	7	102.73	0.39	67	125.93	0.38
192	21.97	0.43	132	47.18	0.42	72	71.53	0.40	12	95.30	0.39	8	103.12	0.39	68	126.32	0.39
191	22.40	0.43	131	47.59	0.41	71	71.93	0.40	11	95.69	0.39	9	103.51	0.39	69	126.70	0.38
190	22.83	0.43	130	48.00	0.41	70	72.33	0.40	10	96.09	0.40	10	103.90	0.39	70	127.08	0.38
189	23.26	0.43	129	48.41	0.41	69	72.73	0.40	9	96.48	0.39	11	104.29	0.39	71	127.46	0.38
188	23.69	0.43	128	48.82	0.41	68	73.13	0.40	8	96.87	0.39	12	104.68	0.39	72	127.85	0.39
187	24.12	0.43	127	49.23	0.41	67	73.53	0.40	7	97.26	0.39	13	105.07	0.39	73	128.23	0.38
186	24.55	0.43	126	49.64	0.41	66	73.93	0.40	6	97.65	0.39	14	105.46	0.39	74	128.61	0.38
185	24.97	0.42	125	50.06	0.42	65	74.33	0.40	5	98.04	0.39	15	105.85	0.39	75	128.99	0.38
184	25.39	0.42	124	50.47	0.41	64	74.73	0.40	4	98.44	0.40	16	106.24	0.39	76	129.38	0.39
183	25.82	0.43	123	50.88	0.41	63	75.13	0.40	3	98.83	0.39	17	106.63	0.39	77	129.76	0.38
182	26.25	0.43	122	51.29	0.41	62	75.53	0.40	2	99.22	0.39	18	107.02	0.39	78	130.14	0.38
181	26.67	0.42	121	51.70	0.41	61	75.93	0.40	1	99.61	0.39	19	107.40	0.38	79	130.52	0.38
180	27.10	0.43	120	52.11	0.41	60	76.33	0.40				20	107.79	0.39	80	130.90	0.38
179	27.52	0.42	119	52.52	0.41	59	76.73	0.40				21	108.18	0.39	81	131.28	0.38
178	27.95	0.43	118	52.92	0.40	58	77.13	0.40				22	108.57	0.39	82	131.67	0.39
177	28.37	0.42	117	53.33	0.41	57	77.52	0.39				23	108.96	0.39	83	132.05	0.38
176	28.80	0.43	116	53.74	0.41	56	77.92	0.40				24	109.35	0.39	84	132.43	0.38
175	29.22	0.42	115	54.15	0.41	55	78.32	0.40				25	109.73	0.38	85	132.81	0.38
174	29.65	0.43	114	54.56	0.41	54	78.72	0.40				26	110.12	0.39	86	133.19	0.38
173	30.07	0.42	113	54.97	0.41	53	79.11	0.39				27	110.51	0.39	87	133.57	0.38
172	30.49	0.42	112	55.38	0.41	52	79.51	0.40				28	110.90	0.39	88	133.95	0.38
171	30.92	0.43	111	55.78	0.40	51	79.91	0.40				29	111.28	0.38	89	134.33	0.38
170	31.34	0.42	110	56.19	0.41	50	80.31	0.40				30	111.67	0.39	90	134.71	0.38
169	31.76	0.42	109	56.60	0.41	49	80.70	0.39				31	112.06	0.39	91	135.09	0.38
168	32.18	0.42	108	57.00	0.40	48	81.10	0.40				32	112.45	0.39	92	135.47	0.38
167	32.61	0.43	107	57.41	0.41	47	81.50	0.40				33	112.83	0.38	93	135.85	0.38
166	33.03	0.42	106	57.82	0.41	46	81.89	0.39				34	113.22	0.39	94	136.23	0.38
165	33.45	0.42	105	58.22	0.40	45	82.29	0.40				35	113.61	0.39	95	136.61	0.38
164	33.86	0.41	104	58.63	0.41	44	82.69	0.40				36	113.99	0.38	96	136.99	0.38
163	34.28	0.42	103	59.04	0.41	43	83.08	0.39				37	114.38	0.39	97	137.37	0.38
162	34.70	0.42	102	59.44	0.40	42	83.48	0.40				38	114.77	0.39	98	137.75	0.38
161	35.12	0.42	101	59.85	0.41	41	83.88	0.40				39	115.15	0.38	99	138.13	0.38
160	35.54	0.42	100	60.26	0.41	40	84.27	0.39				40	115.54	0.39	100	138.51	0.38
159	35.96	0.42	99	60.67	0.41	39	84.67	0.40				41	115.93	0.39	101	138.89	0.38
158	36.38	0.42	98	61.07	0.40	38	85.06	0.39				42	116.31	0.38	102	139.27	0.38
157	36.80	0.42	97	61.48	0.41	37	85.46	0.40				43	116.70	0.39	103	139.65	0.38
156	37.22	0.42	96	61.87	0.41	36	85.85	0.39				44	117.08	0.38	104	140.03	0.38
155	37.63	0.41	95	62.29	0.42	35	86.25	0.40				45	117.47	0.39	105	140.39	0.36
154	38.05	0.42	94	62.69	0.40	34	86.64	0.39				46	117.85	0.38	106	140.77	0.38
153	38.47	0.42	93	63.10	0.41	33	87.04	0.40				47	118.24	0.39	107	141.15	0.38
152	38.89	0.42	92	63.50	0.40	32	87.43	0.39				48	118.62	0.38	108	141.53	0.38
151	39.31	0.42	91	63.91	0.41	31	87.83	0.40				49	119.01	0.39	109	141.91	0.38
150	39.72	0.41	90	64.30	0.39	30	88.22	0.39				50	119.40	0.39	110	142.29	0.38
149	40.14	0.42	89	64.70	0.40	29	88.62	0.40				51	119.78	0.38	111	142.66	0.37
148	40.56	0.42	88	65.11	0.41	28	89.01	0.39				52	120.16	0.38	112	143.04	0.38
147	40.97	0.41	87	65.51	0.40	27	89.40	0.39				53	120.55	0.39	113	143.42	0.38
146	41.39	0.42	86	65.91	0.40	26	89.80	0.40				54	120.93	0.38	114	143.80	0.38
145	41.80	0.41	85	66.31	0.40	25	90.19	0.39				55	121.32	0.39	115	144.18	0.38
144	42.22	0.42	84	66.72	0.41	24	90.59	0.40				56	121.70	0.38	116	144.56	0.38
143	42.64	0.42	83	67.12	0.40	23	90.98	0.39				57	122.09	0.39	117	144.94	0.38
142	43.05	0.41	82	67.52	0.40	22	91.37	0.39				58	122.47	0.38	118	145.32	0.38
141	43.46	0.41	81	67.92	0.40	21	91.77	0.40				59	122.86	0.39	119	145.69	0.37

Note: At 100°C, resistance is 138.50 ohms. (DIN 43 760)

RTD Temperature vs. Resistance Table

For European Curve, Alpha = 0.00385, ITS-90 — 1° Celsius Increments

°C	Ohms	Diff.	°C	Ohms	Diff.	°C	Ohms	Diff.	°C	Ohms	Diff.	°C	Ohms	Diff.	°C	Ohms	Diff.
+120	146.07	0.38	+180	168.48	0.37	+240	190.47	0.36	+300	212.05	0.36	+360	233.21	0.35	+420	253.96	0.34
121	146.45	0.38	181	168.85	0.37	241	190.83	0.36	301	212.40	0.35	361	233.56	0.35	421	254.30	0.34
122	146.82	0.37	182	169.22	0.37	242	191.20	0.37	302	212.76	0.36	362	233.91	0.35	422	254.65	0.35
123	147.20	0.38	183	169.59	0.37	243	191.56	0.36	303	213.12	0.36	363	234.26	0.35	423	254.99	0.34
124	147.58	0.38	184	169.96	0.37	244	191.92	0.36	304	213.47	0.35	364	234.60	0.36	424	255.33	0.34
125	147.95	0.37	185	170.33	0.37	245	192.28	0.36	305	213.83	0.36	365	234.95	0.35	425	255.67	0.34
126	148.33	0.38	186	170.69	0.36	246	192.66	0.38	306	214.19	0.36	366	235.30	0.35	426	256.01	0.34
127	148.71	0.38	187	171.06	0.37	247	193.02	0.36	307	214.55	0.36	367	235.65	0.35	427	256.35	0.34
128	149.08	0.37	188	171.43	0.37	248	193.38	0.36	308	214.90	0.35	368	236.00	0.35	428	256.70	0.35
129	149.46	0.38	189	171.80	0.37	249	193.74	0.36	309	215.26	0.36	369	236.35	0.35	429	257.04	0.34
130	149.83	0.37	190	172.17	0.37	250	194.10	0.36	310	215.61	0.35	370	236.70	0.35	430	257.38	0.34
131	150.21	0.38	191	172.54	0.37	251	194.47	0.37	311	215.97	0.36	371	237.05	0.35	431	257.72	0.34
132	150.58	0.37	192	172.91	0.37	252	194.83	0.36	312	216.32	0.35	372	237.40	0.35	432	258.06	0.34
133	150.96	0.38	193	173.27	0.36	253	195.19	0.36	313	216.68	0.36	373	237.75	0.35	433	258.40	0.34
134	151.34	0.38	194	173.64	0.37	254	195.55	0.36	314	217.03	0.35	374	238.09	0.34	434	258.74	0.34
135	151.71	0.37	195	174.01	0.37	255	195.90	0.35	315	217.39	0.36	375	238.44	0.35	435	259.08	0.34
136	152.09	0.38	196	174.39	0.38	256	196.26	0.36	316	217.73	0.34	376	238.79	0.35	436	259.42	0.34
137	152.46	0.37	197	174.75	0.36	257	196.62	0.36	317	218.08	0.35	377	239.14	0.35	437	259.76	0.34
138	152.84	0.38	198	175.12	0.37	258	196.98	0.36	318	218.44	0.36	378	239.48	0.34	438	260.10	0.34
139	153.21	0.37	199	175.49	0.37	259	197.35	0.37	319	218.79	0.35	379	239.83	0.35	439	260.44	0.34
140	153.58	0.37	200	175.86	0.37	260	197.71	0.36	320	219.15	0.36	380	240.18	0.35	440	260.78	0.34
141	153.95	0.37	201	176.23	0.37	261	198.07	0.36	321	219.50	0.35	381	240.52	0.34	441	261.12	0.34
142	154.32	0.37	202	176.59	0.36	262	198.43	0.36	322	219.85	0.35	382	240.87	0.35	442	261.46	0.34
143	154.71	0.39	203	176.96	0.37	263	198.79	0.36	323	220.21	0.36	383	241.22	0.35	443	261.80	0.34
144	155.08	0.37	204	177.33	0.37	264	199.15	0.36	324	220.56	0.35	384	241.56	0.34	444	262.14	0.34
145	155.46	0.38	205	177.70	0.37	265	199.51	0.36	325	220.91	0.35	385	241.91	0.35	445	262.48	0.34
146	155.83	0.37	206	178.06	0.36	266	199.87	0.36	326	221.27	0.36	386	242.25	0.34	446	262.83	0.35
147	156.21	0.38	207	178.43	0.37	267	200.23	0.36	327	221.62	0.35	387	242.60	0.35	447	263.17	0.34
148	156.58	0.37	208	178.80	0.37	268	200.59	0.36	328	221.97	0.35	388	242.95	0.35	448	263.50	0.33
149	156.96	0.38	209	179.16	0.36	269	200.95	0.36	329	222.32	0.35	389	243.29	0.34	449	263.84	0.34
150	157.33	0.37	210	179.53	0.37	270	201.31	0.36	330	222.68	0.36	390	243.64	0.35	450	264.18	0.34
151	157.71	0.38	211	179.90	0.37	271	201.67	0.36	331	223.03	0.35	391	243.98	0.34	451	264.52	0.34
152	158.08	0.37	212	180.26	0.36	272	202.03	0.36	332	223.38	0.35	392	244.33	0.35	452	264.86	0.34
153	158.45	0.37	213	180.63	0.37	273	202.38	0.35	333	223.73	0.35	393	244.67	0.34	453	265.20	0.34
154	158.83	0.38	214	180.99	0.36	274	202.74	0.36	334	224.09	0.36	394	245.02	0.35	454	265.54	0.34
155	159.20	0.37	215	181.36	0.37	275	203.10	0.36	335	224.45	0.36	395	245.36	0.34	455	265.87	0.33
156	159.56	0.36	216	181.73	0.37	276	203.46	0.36	336	224.80	0.35	396	245.71	0.35	456	266.21	0.34
157	159.94	0.38	217	182.09	0.36	277	203.82	0.36	337	225.15	0.35	397	246.05	0.34	457	266.55	0.34
158	160.31	0.37	218	182.46	0.37	278	204.18	0.36	338	225.50	0.35	398	246.40	0.35	458	266.89	0.34
159	160.68	0.37	219	182.82	0.36	279	204.54	0.36	339	225.85	0.35	399	246.74	0.34	459	267.22	0.33
160	161.05	0.37	220	183.19	0.37	280	204.90	0.36	340	226.21	0.36	400	247.09	0.35	460	267.56	0.34
161	161.43	0.38	221	183.55	0.36	281	205.25	0.35	341	226.56	0.35	401	247.43	0.34	461	267.90	0.34
162	161.80	0.37	222	183.92	0.37	282	205.61	0.36	342	226.91	0.35	402	247.78	0.35	462	268.24	0.34
163	162.17	0.37	223	184.28	0.36	283	205.97	0.36	343	227.26	0.35	403	248.12	0.34	463	268.57	0.33
164	162.54	0.37	224	184.65	0.37	284	206.33	0.36	344	227.61	0.35	404	248.46	0.34	464	268.91	0.34
165	162.91	0.37	225	185.01	0.36	285	206.70	0.37	345	227.96	0.35	405	248.81	0.35	465	269.25	0.34
166	163.28	0.37	226	185.38	0.37	286	207.05	0.35	346	228.31	0.35	406	249.15	0.34	466	269.58	0.33
167	163.66	0.38	227	185.74	0.36	287	207.41	0.36	347	228.66	0.35	407	249.50	0.35	467	269.92	0.34
168	164.03	0.37	228	186.11	0.37	288	207.77	0.36	348	229.01	0.35	408	249.84	0.34	468	270.26	0.34
169	164.40	0.37	229	186.47	0.36	289	208.13	0.36	349	229.36	0.35	409	250.18	0.34	469	270.59	0.33
170	164.77	0.37	230	186.84	0.37	290	208.48	0.35	350	229.72	0.34	410	250.53	0.35	470	270.93	0.34
171	165.14	0.37	231	187.20	0.36	291	208.84	0.36	351	230.07	0.35	411	250.89	0.34	471	271.27	0.34
172	165.51	0.37	232	187.56	0.36	292	209.20	0.36	352	230.42	0.35	412	251.21	0.34	472	271.60	0.33
173	165.88	0.37	233	187.93	0.37	293	209.55	0.35	353	230.77	0.35	413	251.55	0.34	473	271.94	0.34
174	166.25	0.37	234	188.29	0.36	294	209.91	0.36	354	231.12	0.35	414	251.90	0.35	474	272.27	0.33
175	166.62	0.37	235	188.65	0.36	295	210.27	0.36	355	231.47	0.35	415	252.24	0.34	475	272.61	0.34
176	167.00	0.38	236	189.02	0.37	296	210.62	0.35	356	231.81	0.36	416	252.59	0.35	476	272.95	0.34
177	167.37	0.37	237	189.38	0.36	297	210.98	0.36	357	232.16	0.35	417	252.94	0.35	477	273.28	0.33
178	167.74	0.37	238	189.74	0.36	298	211.34	0.36	358	232.51	0.35	418	253.28	0.34	478	273.62	0.34
179	168.11	0.37	239	190.11	0.37	299	211.69	0.35	359	232.86	0.35	419	253.62	0.34	479	273.95	0.33

Note: At 100°C, resistance is 138.50 ohms. (DIN 43 760)

Z-233

https://www.omega.com/techref/pdf/z252-254.pdf

SFU

Resistance temperature detectors

2) For more accurate sensing, the Callendar-Van Dusen equation is used:

For T ≥ 0°C $\quad R(T) = R(0)\left[1 + aT + bT^2\right] \quad [\Omega]$

For T < 0°C $\quad R(T) = R(0)\left[1 + aT + bT^2 + c\left(T - 100\right)T^3\right] \quad [\Omega]$

- Coefficients can be calculated from experiments.
- Also, they are available in standards' tables for various materials.
  - Standard EN 60751, $\alpha = 0.00385$ and the coefficients are

$$a = 3.9083 \times 10^{-3}, b = -5.775 \times 10^{-7} \qquad \boldsymbol{T > 0}$$

$$a = 3.9083 \times 10^{-3}, b = -5.775 \times 10^{-7}, c = -4.183 \times 10^{-12} \quad \boldsymbol{T < 0}$$

- These equations are only needed for ***larger spans*** or if sensing is done at ***low*** or ***high*** temperatures

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Resistance temperature detectors

Example: Wire-spool sensor

- A spool of magnet wire (copper wire insulated with a thin layer of polyurethane) contains *500 m* of wire with a diameter of *0.2 mm*. It is proposed to use the spool as a temperature sensor to sense the temperature in a freezer. The proposed range is between $-45°C$ and $+10°C$. A milliammeter is used to display the temperature by connecting the sensor directly to a 1.5 V battery and measuring the current through it.

a) Calculate the resistance of the sensor and the corresponding currents at the minimum and maximum temperatures.

b) Calculate the maximum power the sensor dissipates.

Note: from the given table, $\sigma_0 = 5.8 \times 10^7 s/m$, $\alpha = 0.0039/°C$ at $T_0 = 20°C$

Material	Conductivity[1] σ [S/m]	Temperature coefficient[3] of resistance [per °C]
Copper (Cu)	5.8×10^7	0.0039
Carbon (C)	3.0×10^5	−0.0005

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Resistance temperature detectors

Solution:

$$R(T) = \frac{l}{\sigma_0 S}(1 + \alpha[T - 20^\circ])\ [\Omega]$$

$$R(-45^\circ) = \frac{500}{5.8 \times 10^7 \times \pi \times (0.0001)^2}(1 + 0.0039[-45 - 20^\circ]) = 204.84\,\Omega.$$

$$R(+10^\circ) = \frac{500}{5.8 \times 10^7 \times \pi \times (0.0001)^2}(1 + 0.0039[10 - 20^\circ]) = 263.7\,\Omega$$

- The resistance changes from 204.84 Ω at -45 °C to 263.7 Ω at 10 °C.
- The currents are

$$I(-45^\circ) = \frac{1.5}{204.84} = 7.323 \text{ mA} \qquad I(+10^\circ) = \frac{1.5}{263.7} = 5.688 \text{ mA}$$

- The power dissipated is

$$P(+10^\circ) = I^2R = (5.688 \times 10^{-3})^2 \times 263.7 = 8.53 \text{ mW}$$

$$P(-45^\circ) = I^2R = (7.323 \times 10^{-3})^2 \times 204.84 = 10.98 \text{ mW}$$

- The power is **low** which is *ideal* for temperature sensors since power dissipated in the sensor can lead to *errors* due to self heating if it is high.

SFU

Resistance temperature detectors

Example2: Wire RTD resistance and sensitivity

- A wire-wound RTD sensor is made of pure platinum wire, 0.1 mm in diameter, to have a resistance of 25 Ω at 0 °C. Assume here that the TCR is constant with temperature.

a) Find the necessary length for the wire.

b) Find the resistance of the RTD at 100

c) Find the sensitivity of the sensor in ohms/degree Celsius

Solution:

From the table, $\sigma_0 = 9.4 \times 10^6 s/m$ at $T_0 = 20$°C, and $\alpha = 0.003926/$°C at $T_0 = 0$°C

a)

$$R(T) = \frac{l}{\sigma_0 S}(1 + \alpha[T - 20^\circ])\ [\Omega]$$

$$25 = \frac{l}{9.4 \times 10^6 \times \pi \times (0.05 \times 10^{-3})^2}(1 + 0.003926[0 - 20]) = 12.48154l\ [\Omega]$$

$$l = \frac{25}{12.48154} = 2.003 \text{ m}$$

Resistance temperature detectors

Solution:

b)

$$R(100\,^{\circ}\mathrm{C}) = \frac{2.003}{9.4 \times 10^6 \times \pi \times (0.05 \times 10^{-3})^2}(1 + 0.003926[100 - 20]) \;= 35.652\ \Omega$$

c)

Sensitivity is the slope of transfer function which means the amount of change in resistance by increasing the temperature by 1 °C

$$R(T+1) - R(T) = \frac{l}{\sigma_0 S}(1 + \alpha[T + 1 - 20^{\circ}]) - \frac{l}{\sigma_0 S}(1 + \alpha[T - 20^{\circ}]) \;= \frac{l\alpha}{\sigma_0 S}\ [\Omega]$$

$$\Delta R = \frac{l\alpha}{\sigma_0 S} = \frac{2.003 \times 0.003926}{9.4 \times 10^6 \times \pi \times (0.05 \times 10^{-3})^2} = 0.1065\ \Omega$$

- The sensitivity is therefore 0.1065 Ω /°C
- Check: Since the resistance is linear with temperature, the sensitivity is the same everywhere and thus we can write the resistance at 100 °C as

$$R(100\,^{\circ}\mathrm{C}) = R(0\,^{\circ}\mathrm{C}) + 100 \times \Delta R = 25 + 100 \times 0.1065 = 35.65\ \Omega$$

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Resistance temperature detectors

Example 3: RTD representation and accuracy

- A platinium RTD with nominal resistance of 100 Ω at 0 °C is specified for the range from $-200°C$ to $+600°C$. The engineer has the option of using the approximate transfer function (linear) or the exact transfer function in (polynomial). Assume $\alpha = 0.00385/°C$

a) Calculate the error incurred by using the approximate transfer function at the extremes of the range.

b) What are the errors if the range used is from $-50°C$ to $+100°C$

From standard EN 60751, $\alpha = 0.00385$ and the coefficients are

$$a = 3.9083 \times 10^{-3}, b = -5.775 \times 10^{-7} \qquad \boldsymbol{T > 0}$$

$$a = 3.9083 \times 10^{-3}, b = -5.775 \times 10^{-7}, c = -4.183 \times 10^{-12} \quad \boldsymbol{T < 0}$$

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Resistance temperature detectors

Solution:

a) **linear TF**

$$R(600\ ^\circ\mathrm{C}) = R(0)[1 + \alpha T] = 100[1 + 0.00385 \times 600] = 331\ \Omega$$

$$R(-200\ ^\circ\mathrm{C}) = 100[1 - 0.00385 \times 200] = 23\ \Omega$$

nonlinear TF

$$R(600\ ^\circ\mathrm{C}) = R(0)[1 + aT + bT^2]$$

$$100[1 + 3.9083 \times 10^{-3} \times 600 - 5.775 \times 10^{-7} \times 600^2] = 313.708\ \Omega$$

$$R(-200\ ^\circ\mathrm{C}) = R(0)\left[1 + aT + bT^2 + c(T - 100)T^3\right] \quad [\Omega]$$

$$100[1 + 3.9083 \times 10^{-3} \times (-200) - 5.775 \times 10^{-7} \times 200^2$$

$$-4.183 \times 10^{-12} \times (-300) \times (-200)^3] = 18.52\Omega$$

- The resistance calculated with the approximate formula is higher by 5.51% at 600°C and higher by 24.19% at -200 °C.
- These deviations ***are not acceptable*** and use of the Callendar–Van Dusen relations is *essential*.

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Resistance temperature detectors

Solution:

b) **linear TF**

$$R(100\,^{\circ}\mathrm{C}) = R(0)[1 + \alpha T] = 100[1 + 0.00385 \times 100] = 138.5\ \Omega$$

$$R(-50\,^{\circ}\mathrm{C}) = 100[1 - 0.00385 \times 50] = 80.75\ \Omega$$

nonlinear TF

$$R(100\,^{\circ}\mathrm{C}) = 100[1 + 3.9083 \times 10^{-3} \times 100 - 5.775 \times 10^{-7} \times 100^2] = 138.5055\ \Omega$$

$$R(-50\,^{\circ}\mathrm{C}) = 100[1 + 3.9083 \times 10^{-3} \times (-50) - 5.775 \times 10^{-7} \times 50^2$$

$$-4.183 \times 10^{-12} \times (-150) \times (-50)^3] = 80.3063\Omega$$

- The resistance calculated with the approximate formula is only 0.0397% lower at 100°C and lower by 0.552% at -50 °C.
- These deviations are ***acceptable*** and the *approximate formula can be* used.

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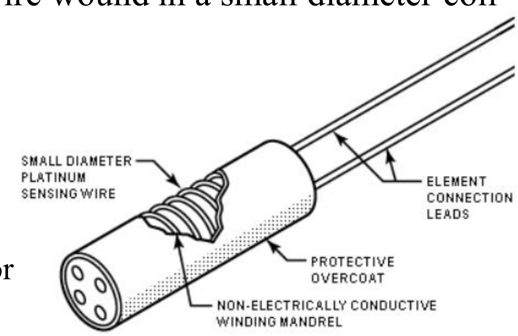
Construction - Wire RTD

- Careful to minimize the effect of tension on wires in designing RTDs which has the same effect on resistance as a change in temperature
- A characteristic property of wire RTDs is their ***relatively low resistance***
  - High resistances would require very long wires or very thin wires.
  - Another consideration is cost.
- Satisfactory resistance for wire sensors is from a ***few ohms*** to a ***few tens of ohms***
- Wire is made of a fairly ***thin, uniform*** wire wound in a small diameter coil
- Coil is supported on a suitable support such as ***mica*** or ***glass***.
- Wire and coil are enclosed in a ***glass***, ***ceramic*** or ***highly conductive metal***
  - Allow better heat transfer to the sensing wire and so, faster response of the sensor



Platinum RTD Probe Construction: Elements (rdfcorp.com)

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Material - Wire RTD

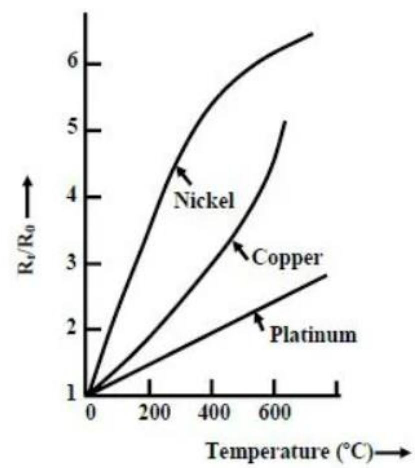
- RTDs are typically made out of ***Platinum*** wire.
- ***Nickel & Copper*** have been used, but for RTDs, Platinum is superior to the other metals.

Platinum - used for precision applications

- Chemically stable at high temperatures
- Resists oxidation
- Can be made into thin wires of high chemical purity
- Resists corrosion
- Can withstand severe environmental conditions.
- Useful to about 800 °C and down to below –250 °C.
- Very sensitive to strain
- Sensitive to chemical contaminants

Material - Wire RTD

- **Nickel**
  - ➢ Less-demanding applications and cheaper
  - ➢ Can be used from about -100 °C to about 500 °C, but its R–T curve becomes non-linear at temperatures above 300 °C
- **Copper**
  - ➢ Less-demanding applications and cheaper
  - ➢ Wire length needed is long (high conductivity)
  - ➢ Reduced temperature range (copper only works up to about 300 °C)
  - ➢ Oxidizes and it cannot be used over 150 °C
  - ➢ Not suitable for corrosive environments (unless properly protected)

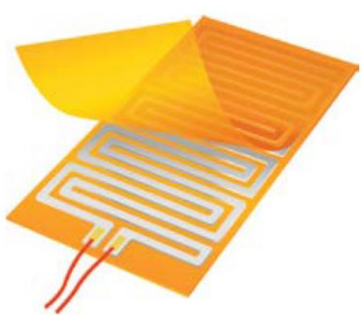


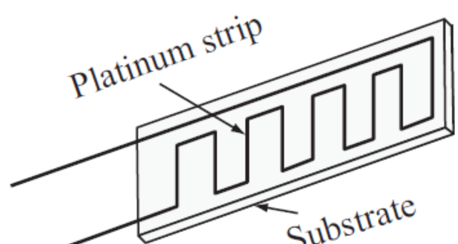
 Resistance Temperature Detector or RTD | Construction and Working Principle | Electrical4U

Thin Film RTD

Thin film sensors:

- Produced by depositing a thin layer of a suitable material (platinum or its alloys) on electrically non-conducting, and thermally conducting ceramic
- Etched to form a long strip and potted in epoxy or glass to protect it.
- Small and relatively inexpensive (some are only a few mm^2)
- Often the choice in modern sensors especially when the very high precision of Platinum wire sensors is not needed.





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Thin Film RTD

Advantages of wire-wound resistors:

- High accuracy along the entire temperature range, required in certain laboratory settings or for applications like custody transfer

Disadvantages of wire-wound resistors

- Not vibration resistant
- Larger footprint (around 25mm, or 1 inch) in length
- As much as 10 times more expensive than a thin-film resistor

Advantages of thin-film resistors

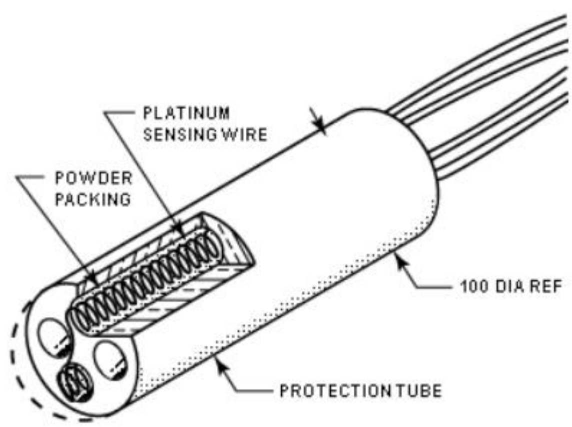
- Compact size (around 3mm, or 1/8-inch) in length
- Vibration resistant, thanks to their smaller mass and no moving parts, making them ideal for use in compressors and bearing applications
- About 1/10th of the cost of a wire-wound resistor

Disadvantages of thin-film resistors

- Loss of accuracy at low and high temperatures

Coiled Element RTD

- This "strain-free" design allows the sensing wire to expand and contract freely.
- The sensing element is a small coil of platinum wire that resembles a filament in light bulb.
- The coil is inserted into bores of the mandrel and packed with a very finely ground ceramic powder.
- This permits the sensing wire to move, while still remaining in good thermal contact with the process.



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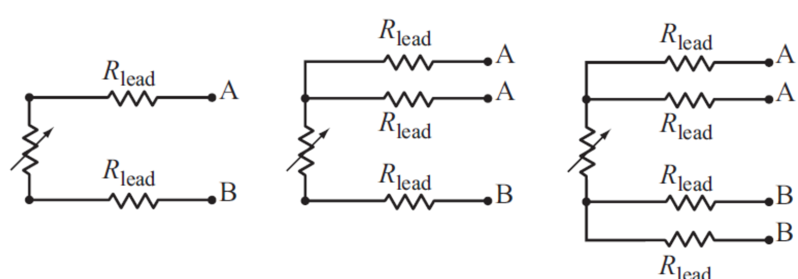
Connection of RTD

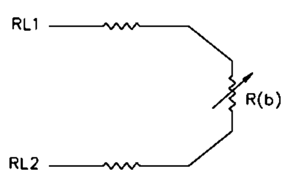
- RTD measurements are subject to errors due to the connecting wires resistance and temperature variations along these wires

- In ***low resistance RTDs***, the resistance of the *lead wires* also changes with temperature, and can add to errors in the sensing circuit as these resistances are ***not negligible*** (except in *high-resistance thin-film RTDs*).

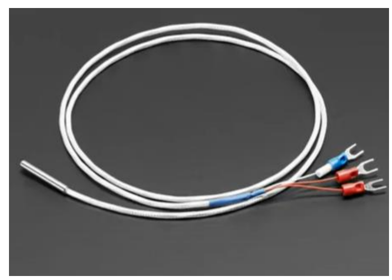
- Because of this, some commercial sensors come in ***two-***, ***three-***, or ***four wire*** configurations to facilitate compensation for the lead wires
  - Two-wire configurations ***cannot*** be compensated
  - Three- and four-wire sensors ***allow*** compensation of the lead resistance and should be used when *high precision* is essential.

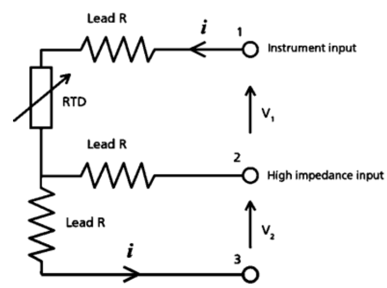


Connection of RTD



Measured resistance $R_t = R_l + R_2 + R_b$





$$V_1 = i(RTD + 2 \times [lead\ wire\Omega])$$

$$V_2 = i(2 \times lead\ wire\Omega)$$

$$V_2 - V_1 = i(RTD)$$

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Self heat in RTDs

- RTDs are subject to errors due to ***increases*** in their own temperature produced by the heat generated in them by the ***current*** used to measure their resistance.

- Applicable to wire-wound or thin film sensors

- Power dissipated: $P_d = I^2R$ (I is current and *R* the sensor's resistance)

- Self heat depends on size, construction and environment
  - Lower in large elements, higher in small elements
  - Environmental factors (moving air or standing air, etc.) affect significantly
  - Important to lower the current as much as possible

- Given as temperature rise per unit power (°C/mW) or power needed to raise temperature (mW/°C) by manufacturer
  - Self-heat errors are of the order of 0.01 °C/mW to 0.2 °C/mW

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Self heat in RTDs

Example: Self heat in RTDs

- A 100 Ω (at 0 °C) platinum RTD operates between -200°C to +850 °C. Its self-heat is provided in its data sheet as 0.08 °C /mW in air (typically, this value is given at a low airspeed of 1 m/s). Calculate the maximum error expected due to self-heat if

a) Resistance is measured by applying a constant voltage of 1 V across the sensor.

b) Resistance is measured by applying a constant current of 10 mA through the sensor.

$$a = 3.9083 \times 10^{-3}, b = -5.775 \times 10^{-7} \qquad \boldsymbol{T > 0}$$

$$a = 3.9083 \times 10^{-3}, b = -5.775 \times 10^{-7}, c = -4.183 \times 10^{-12} \quad \boldsymbol{T < 0}$$

Solution:

a)

$$\begin{aligned} R(-200\,^\circ\mathrm{C}) &= R(0)[1 + aT + bT^2 + c(T-100)T^3] \\ &= 100[1 + 3.9083 \times 10^{-13} \times (-200) - 5.775 \times 10^{-7} \times 200^2 \\ &\quad - 4.183 \times 10^{-12} \times (-200-100) \times (-200)^3] = 18.52\,\Omega \end{aligned}$$

$$\begin{aligned} R(850\,^\circ\mathrm{C}) &= R(0)[1 + aT + bT^2] \\ &= 100[1 + 3.9083 \times 10^{-3} \times 850 - 5.775 \times 10^{-7} \times 850^2] \\ &= 390.48\,\Omega. \end{aligned}$$

$$P(-200\,^\circ\mathrm{C}) = \frac{V^2}{R} = \frac{1}{18.52} = 54\ \mathrm{mW} \qquad P(850\,^\circ\mathrm{C}) = \frac{V^2}{R} = \frac{1}{390.48} = 2.56\ \mathrm{mW}$$

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Self heat in RTDs

a)

$$\text{error at} - 200\ ^\circ\text{C is } 54 \times 0.08 = 4.32\ ^\circ\text{C}$$

$$\text{error at } 850\ ^\circ\text{C is } 2.56 \times 0.08 = 0.205\ ^\circ\text{C}$$

- The maximum error occurs at ***-200 ℃*** and equals ***4.3 ℃*** or ***2.15%***.
- At the high end of the span the error is only ***0.2 ℃***.

b)

$$P(-200^\circ\text{C}) = I^2R = \left(10 \times 10^{-3}\right)^2 \times 18.52 = 1.85\ \text{mW}$$

$$P(850\ ^\circ\text{C}) = I^2R = \left(10 \times 10^{-3}\right)^2 \times 390.48 = 39\ \text{mW}$$

$$\text{error at} - 200\ ^\circ\text{C} = 1.85 \times 0.08 = 0.148\ ^\circ\text{C}.$$
$$\text{error at } 850\ ^\circ\text{C} = 39 \times 0.08 = 3.12\ ^\circ\text{C}$$

- The maximum error occurs at ***850 ℃*** and equals ***3.12 ℃*** or ***0.37%***.
- Both methods are used and in both the errors vary with temperature.
- Use of a ***current*** source reduces the errors throughout the temperature range.
- To *reduce* the error, the current can *be reduced*, but it *cannot be too small*, because of difficulties in measurements as well as noise may be encountered.

SFU

Response Time in RTDs

- Response of most ***temperature sensors*** is slow, especially if they are physically large.
- Provided as part of data sheet
- Given in air or in water or both, moving or stationary
- Given as time to reach 90%, 50% (or other) of steady state
    - 50% of steady state means the sensor has reached a temperature equal to its initial value plus 50% of the step.
- Generally slow
- Wire RTDs are slower (because of their physical size)
- Typical values 0.5 sec in water to 100 sec in moving air

SFU

Silicon Resistive Sensors

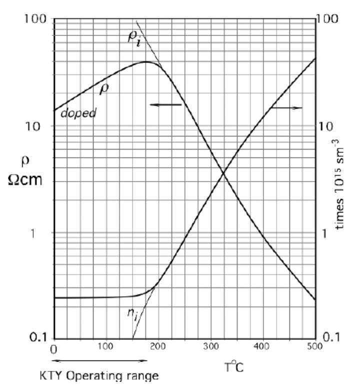
- **Valence electrons** are those bound to atoms and hence not free to move
- **Conduction electrons** are free to move and affect the current through the semiconductor.

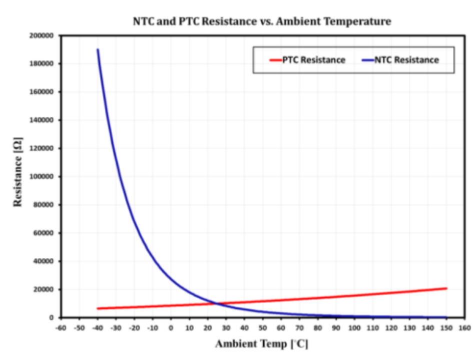
- For an electron to move into the *conduction band*, it must acquire ***additional energy*** which is called ***band gap energy*** and is *material dependent*
  - ➢ This additional energy comes from ***heat***, ***light***, ***nuclear***, ***electromagnetic***

- The ***higher*** the temperature, the ***higher*** the number of electrons available and hence the ***higher*** the current that can flow through the device (i.e., the ***lower*** its resistance).
  - ➢ As temperature increases, the resistance decreases
  - ➢ Pure semiconductors such as silicon typically have NTC characteristics

Silicon Resistive Sensors

- Semiconductors are ***rarely*** used as pure (intrinsic) materials.
- Impurities are introduced into the intrinsic material in a process called ***doping***.
- If silicon dope with an n-type impurity such as arsenic (As) or antimony (Sb), the reverse effect (PTC) is observed below a certain temperature.
  - For n-type silicon, a PTC is observed below about 200°C (NTC above)
  - PTC silicon resistive (Cylister), are mainly used for fuses
  - while NTC sensors are just used for temperature sensors





https://www.es.ele.tue.nl/education/SensorsActuators/files/sensors/physics/03-thermoresistive-sensors

Silicon Resistive Sensors

- PTC Silicon resistive sensors can operate in a ***limited range*** of temperatures like most semiconductors devices based on silicon
- Maximum range is between –55°C to +150°C.
- Typical range: – 45°C to +85°C or 0°C to +80°C
- Resistance: typically 1kΩ at 25°C.
- Made as a small chip with two electrodes and encapsulated in epoxy, etc
- Resistance is calculated using the Callendar-Van Dusen Equation

$$R(T) = R(0)\left[1 + a\left(T - T_{\text{ref}}\right) + b\left(T - T_{\text{ref}}\right)^2 + HOT\right] \quad [\Omega]$$

HOT stands for "higher order terms" indicating that additional coefficients may be used to improve representation