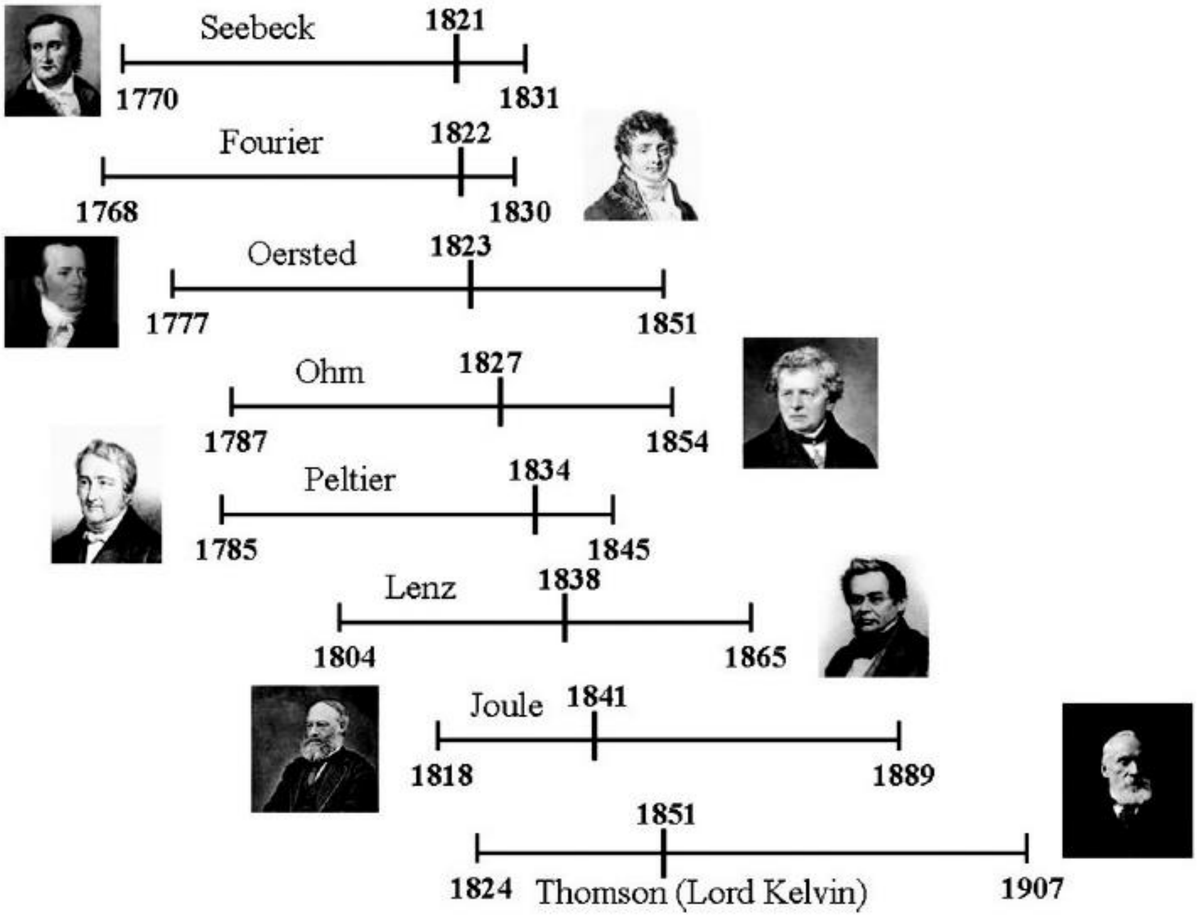
Semiconductor Sensors:

Ch5: Temperatures Sensors Cont.

Lecturer: Dr. Navid Alaei-Sheini
Assistant Professor of Electrical Enginnering
Shahid Chamran University of Ahvaz

آثار ترموالکتریک

Thermoelectric effects: The phenomena linking thermal energy transport and electrical currents in solid materials are collectively known as *thermoelectric effects*.



Chronogram showing the portraits and life span of the main characters in the origins of thermoelectric research. The ticks indicate the date when the corresponding thermoelectric phenomenon was first reported.

Maciá, Enrique, ed. Thermoelectric Materials: Advances and Applications. CRC Press, 2015.

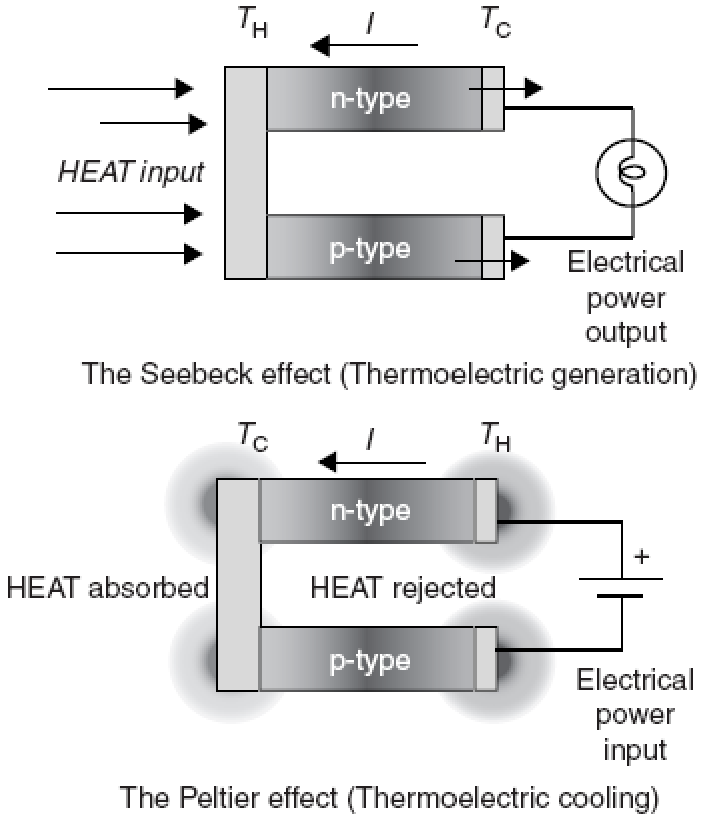
آثار ترموالکتریک

Seebeck Effect

Peltier Effect

Thomson Effect

The Kelvin Relationships



Thermoelectric generator (upper); thermoelectric refrigerator (lower).

Rowe, David Michael, ed. Thermoelectrics handbook: macro to nano. CRC press, 2005.

Seebeck Effect

اثر سیبک

The thermometric effects which underlie thermoelectric energy conversion can be conveniently discussed with reference to the schematic of a thermocouple shown in Figure 1.2. It can be considered as a circuit formed from two dissimilar conductors, a and b (referred to in thermoelectrics as thermocouple legs, arms, thermoelements, or simply elements and sometimes as pellets by device manufacturers) which are connected electrically in series but thermally in parallel. If the junctions at A and B are maintained at different temperatures T_1 and T_2 and $T_1 > T_2$ an open circuit electromotive force (emf), V is developed between C and D and given by $V = \alpha(T_1 - T_2)$ or $\alpha = V/\Delta T$, which defines the differential Seebeck coefficient α_{ab} between the elements a and b. For small temperature differences the relationship is linear. Although by convention α is the symbol for the Seebeck coefficient, S is also sometimes used and the Seebeck coefficient referred to as the thermal emf or thermopower. The sign of α is positive if the emf causes a current to flow in a clockwise direction around the circuit and is measured in V/K or more often in $\mu V/K$.

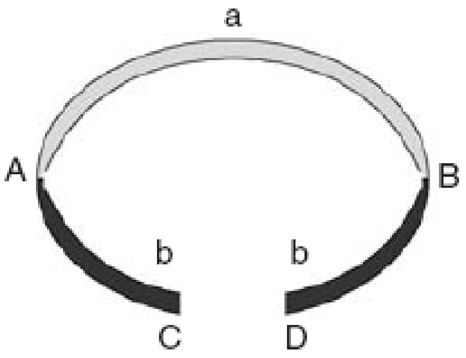
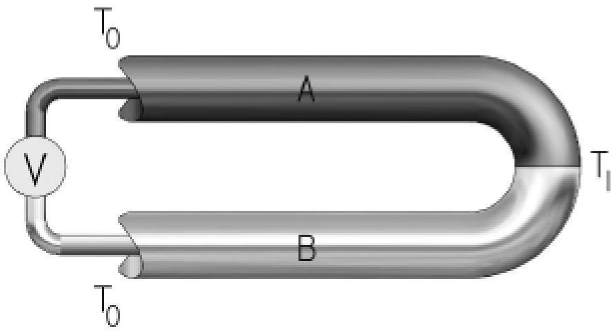


FIGURE 1.2 Schematic basic thermocouple.

Rowe, David Michael, ed. Thermoelectrics handbook: macro to nano. CRC press, 2005.

Seebeck Effect

اثر سیبک



Schematic View of a Thermocouple

$$V = S_A(T_1 - T_0) + S_B(T_0 - T_1)$$

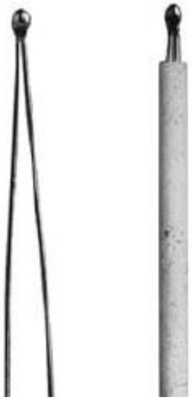
contribution from conductor A *contribution from conductor B*

$$V = S_A(T_1 - T_0) - S_B(T_1 - T_0)$$

$$V = (S_A - S_B)(T_1 - T_0)$$

$$S_{AB} = S_A - S_B$$

$$V = S_{AB}(T_1 - T_0)$$



(a) Conventional metal metal/alloy thermocouple

[Thermoelectrics handbook: macro to nano. CRC press, 2005]

Table 1.1 Seebeck coefficient values of different materials at $T = 273$ K

Metal	S (μVK^{-1})	Metal	S (μVK^{-1})
Ni	−18.0	Pd	−9.00
Pt	−4.45	Pb	−1.15
V	+0.13	W	+0.13
Rh	+0.48	Ag	+1.38
Cu	+1.70	Au	+1.79
Mo	+4.71	Cr	+18.0

[Maciá, Enrique, ed. Thermoelectric Materials: Advances and Applications. CRC Press, 2015]

T. W. Kerlin and M. Johnson. *Practical thermocouple thermometry*. Instrument Society of America, 1999.

Peltier Effect

اثر پلتیر

If in Figure 1.2 the reverse situation is considered with an external emf source applied across C and D and a current I flows in a clockwise sense around the circuit then a rate of heating q occurs at one junction between a and b and a rate of cooling $-q$ occurs at the other. The ratio of I to q defines the Peltier coefficient given by $\pi = I/q$, is positive if A is heated and B is cooled, and is measured in watts per ampere or in volts.

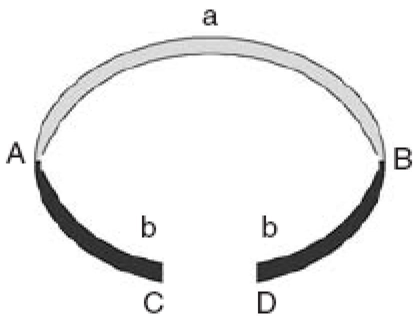
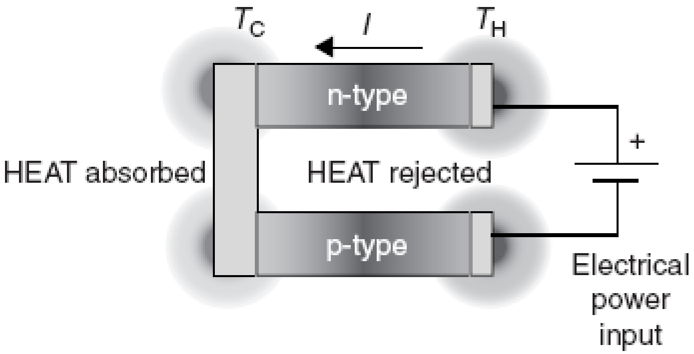


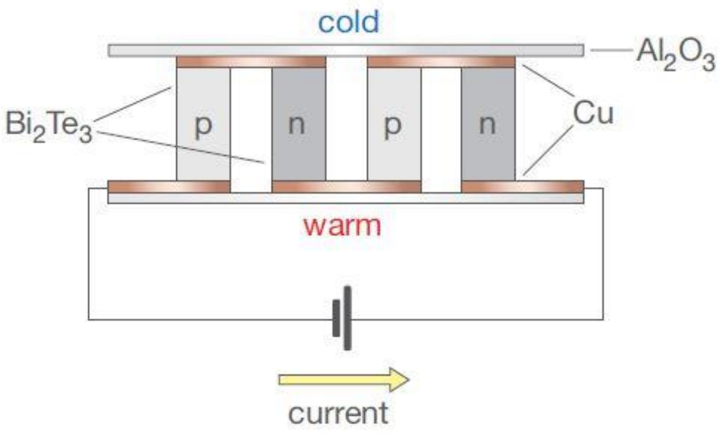
FIGURE 1.2 Schematic basic thermocouple.



The Peltier effect (Thermoelectric cooling)

Rowe, David Michael, ed. Thermoelectrics handbook: macro to nano. CRC press, 2005.

نمونه های از سردکن پلتیر



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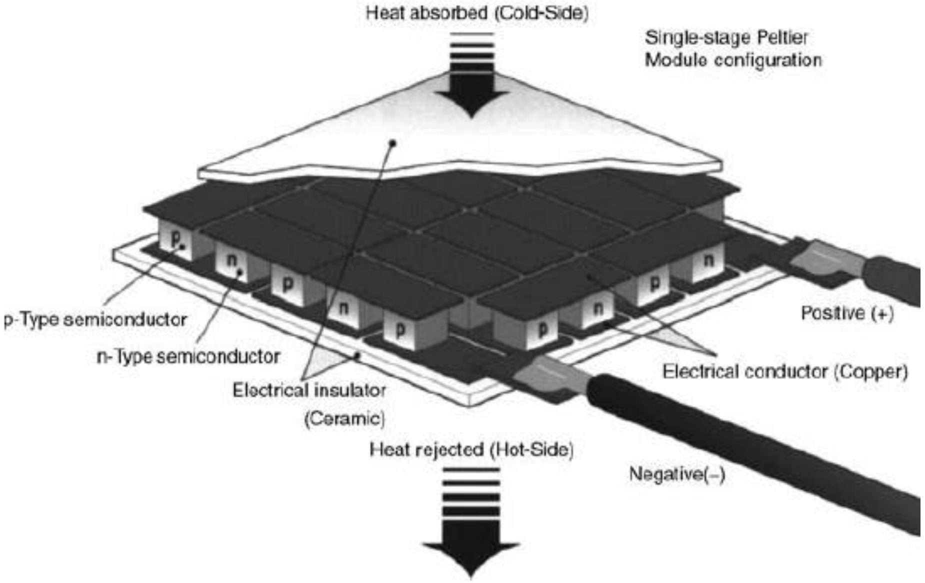
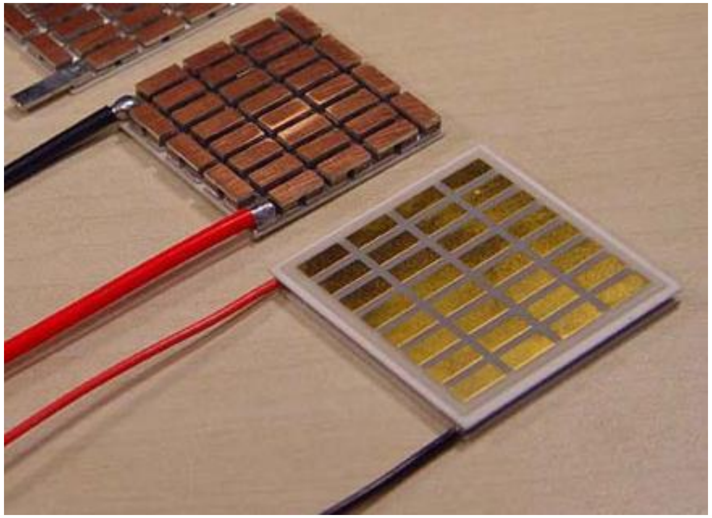


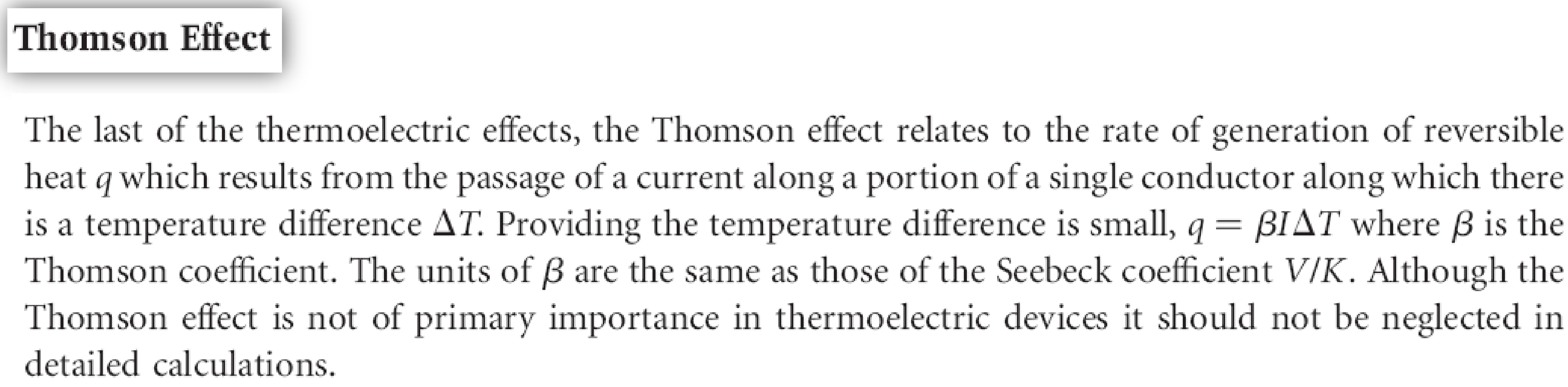
FIGURE 1.11 Cutaway of a typical Peltier cooler.



http://www.huimao.com/product/showproduct.php?id=23&lang=en

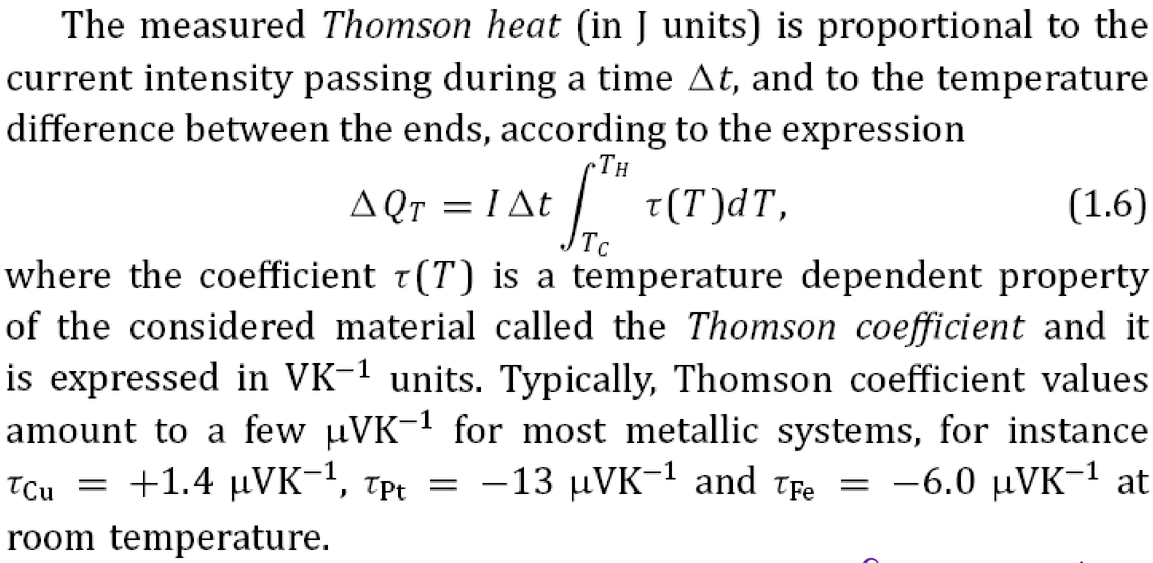
Rowe, David Michael, ed. Thermoelectrics handbook: macro to nano. CRC press, 2005.

اثر تامسون



Thomson Effect

The last of the thermoelectric effects, the Thomson effect relates to the rate of generation of reversible heat q which results from the passage of a current along a portion of a single conductor along which there is a temperature difference ΔT. Providing the temperature difference is small, $q = \beta I \Delta T$ where β is the Thomson coefficient. The units of β are the same as those of the Seebeck coefficient V/K. Although the Thomson effect is not of primary importance in thermoelectric devices it should not be neglected in detailed calculations.



The measured *Thomson heat* (in J units) is proportional to the current intensity passing during a time Δt, and to the temperature difference between the ends, according to the expression

$$\Delta Q_T = I\,\Delta t \int_{T_C}^{T_H} \tau(T)\,dT, \tag{1.6}$$

where the coefficient $\tau(T)$ is a temperature dependent property of the considered material called the *Thomson coefficient* and it is expressed in VK^{-1} units. Typically, Thomson coefficient values amount to a few $\mu\mathrm{VK}^{-1}$ for most metallic systems, for instance $\tau_{\mathrm{Cu}} = +1.4\ \mu\mathrm{VK}^{-1}$, $\tau_{\mathrm{Pt}} = -13\ \mu\mathrm{VK}^{-1}$ and $\tau_{\mathrm{Fe}} = -6.0\ \mu\mathrm{VK}^{-1}$ at room temperature.

معنی ضریب تامسون مثبت و منفی چیست؟

Rowe, David Michael, ed. Thermoelectrics handbook: macro to nano. CRC press, 2005.
Maciá, Enrique, ed. Thermoelectric Materials: Advances and Applications. CRC Press, 2015.

آثار ترموالکتریک- ارتباط ضرایب

The Kelvin Relationships

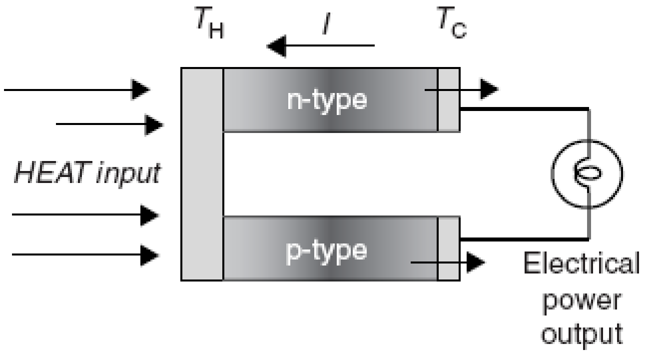
The above three thermoelectric coefficients are elated by the Kelvin relationships:

$$\alpha_{\mathrm{ab}} = \pi_{\mathrm{ab}}/T \quad \text{and} \quad \frac{\mathrm{d}\alpha_{\mathrm{ab}}}{\mathrm{d}T} = \frac{\beta_{\mathrm{a}} - \beta_{\mathrm{b}}}{T}$$

These relationships can be derived using irreversible thermodynamics. Their validity has been demonstrated for many thermoelectric materials and it is assumed that they hold for all materials used in thermoelectric applications.

Rowe, David Michael, ed. Thermoelectrics handbook: macro to nano. CRC press, 2005.

ضریب شایستگی مواد ترموالکتریک



The Seebeck effect (Thermoelectric generation)

The efficiency of the generator is given by

$$\phi = \frac{\text{energy supplied to the load}}{\text{heat energy absorbed at hot junction}}$$

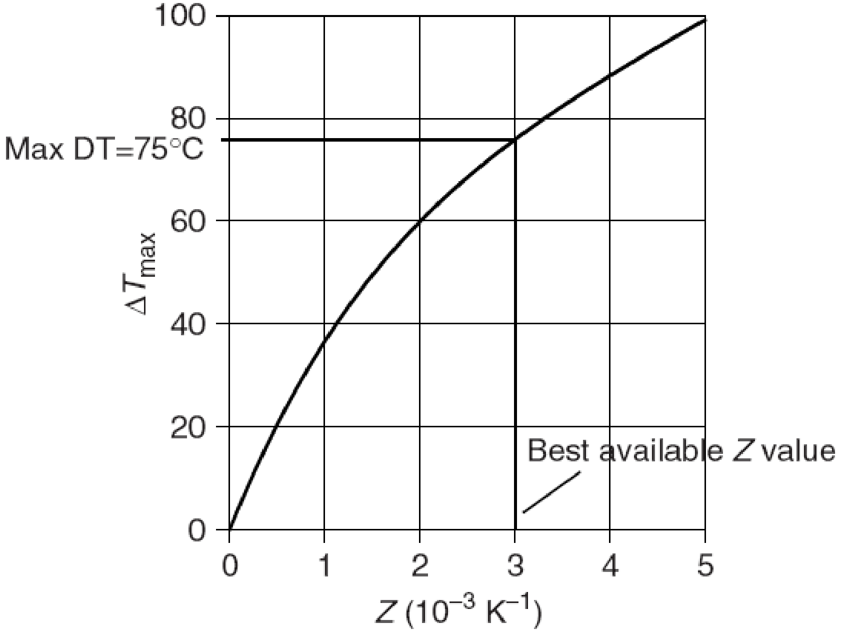
$$Z_c(\text{the figure-of-merit of the couple}) = \frac{\alpha_{\text{ab}}^2}{R\lambda'}$$

where λ' is the thermal conductance of a and b in parallel and R is the series resistance of a and b.

$$Z = \frac{\alpha^2\sigma}{\lambda}$$

Rowe, David Michael, ed. Thermoelectrics handbook: macro to nano. CRC press, 2005.

مواد ترموالکتریک



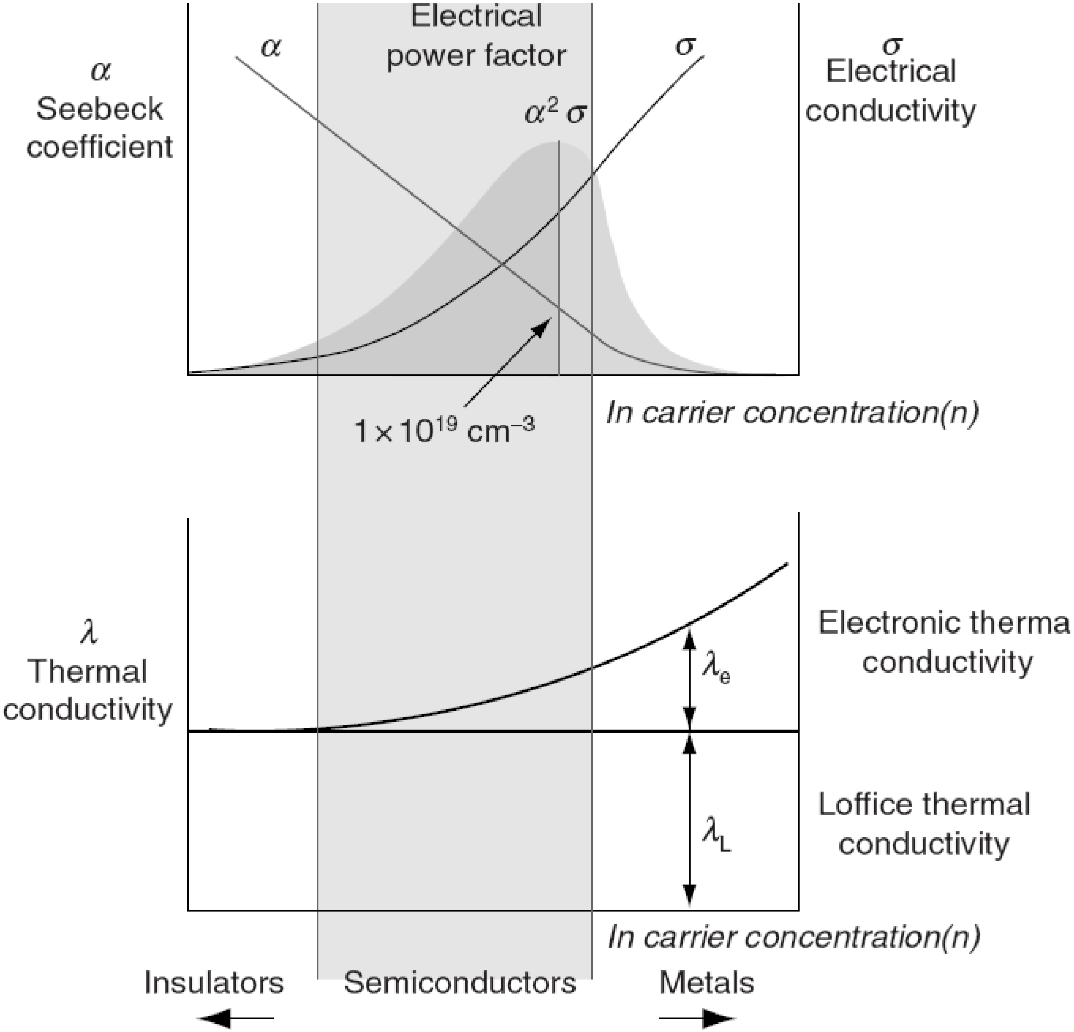
Theoretical maximum temperature difference of a thermoelectric module plotted against Z

Because the figure-of-merit varies with temperature a more meaningful measure of performance is the dimensionless figure-of-merit ZT where T is absolute temperature However, only those materials which possess a ZT > 0.5 are usually regarded as thermoelectric materials.

Rowe, David Michael, ed. Thermoelectrics handbook: macro to nano. CRC press, 2005.

مواد ترموالکتریک

$$Z = \frac{\alpha^2 \sigma}{\lambda}$$



Schematic dependence of electrical conductivity, Seebeck coefficient, power factor, and thermal conductivity on concentration of free carriers.

Rowe, David Michael, ed. Thermoelectrics handbook: macro to nano. CRC press, 2005.

مواد ترموالکتریک

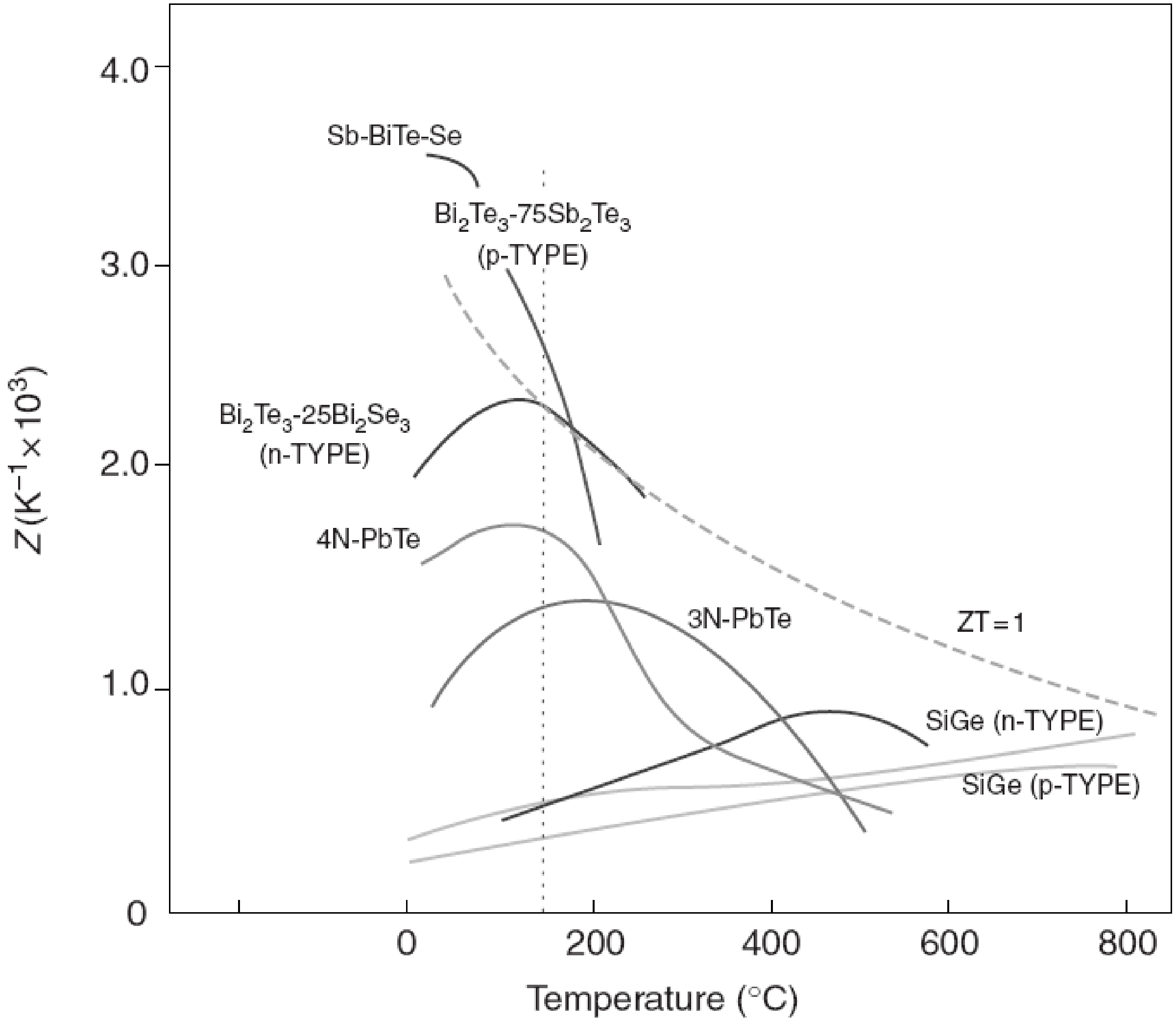
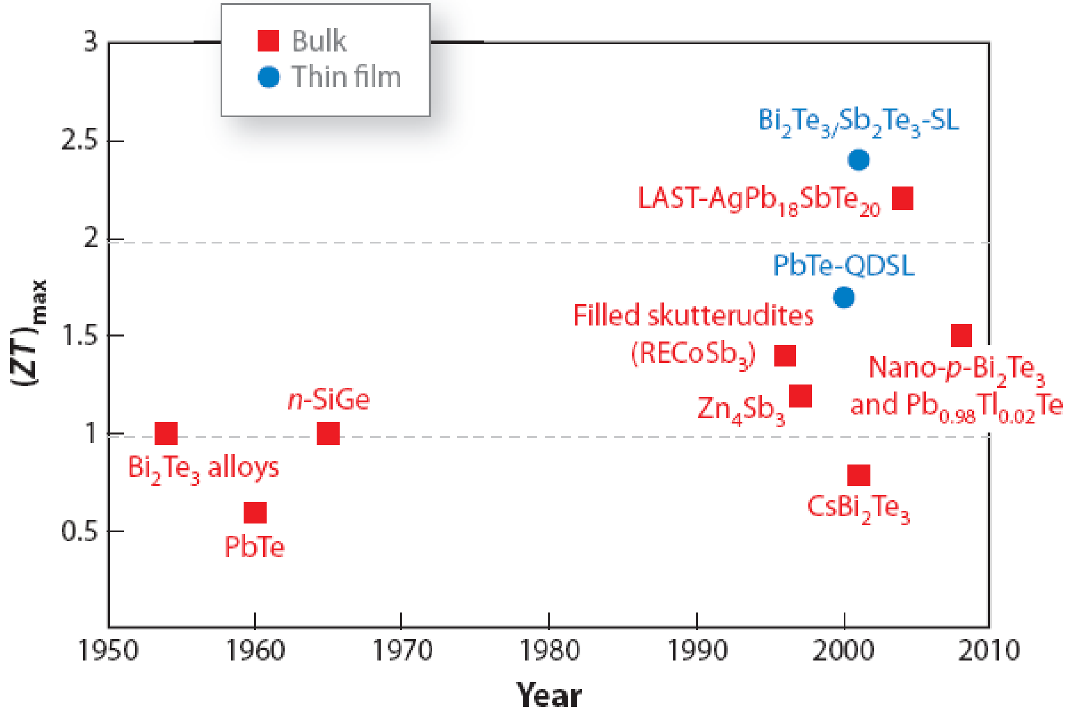


FIGURE 1.8 Performance of the established thermoelectric materials.

Rowe, David Michael, ed. Thermoelectrics handbook: macro to nano. CRC press, 2005.

مواد ترموالکتریک- علت توجه شدید به ترموالکتریک در سالهای اخیر



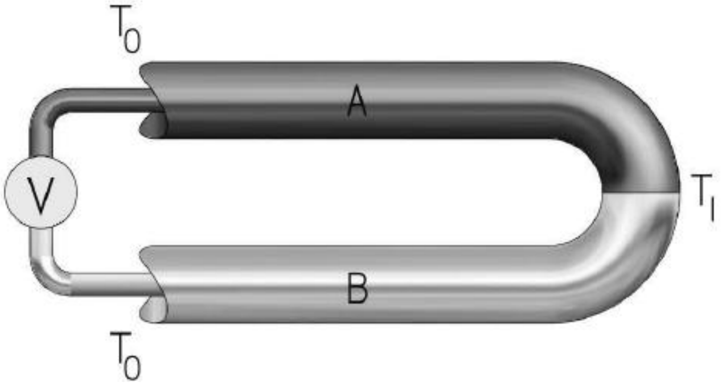
Over the past 10–15 years, there have been significant advances in the scientific understanding as well as in the performance of thermoelectric (TE)materials. TE materials can be incorporated into power generation devices that are designed to convert waste heat into useful electrical energy. The conversion of waste heat into electrical energy will certainly play a role in our current challenge for alternative energy technologies to reduce our dependence on fossil fuels and to reduce greenhouse gas emissions.

Tritt, Terry M. "Thermoelectric phenomena, materials, and applications." Annual review of materials research 41 (2011): 433-448.

دماسنجی با ترموکوپل

$$V = S_A(T_1 - T_0) + S_B(T_0 - T_1)$$

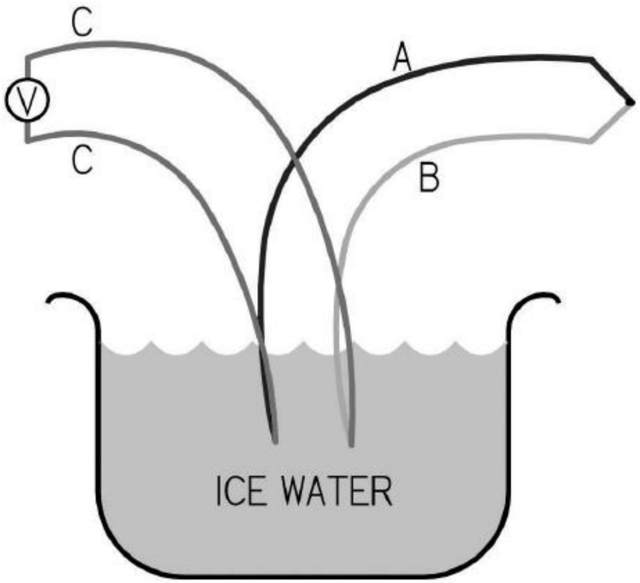
contribution from conductor A *contribution from conductor B*



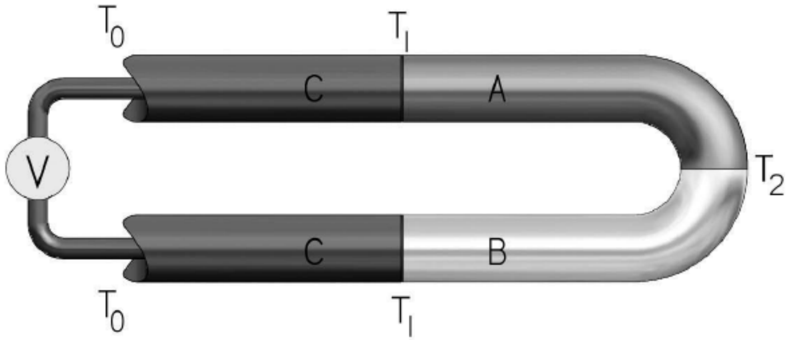
The Law of Thermocouple Thermometry: The emf produced by a segment of parallel dissimilar wires that experiences a temperature difference across the segment is proportional to the temperature difference. The total emf produced by the total circuit is the algebraic sum of the emfs produced by each segment between the open end and the junction of the wires.

T. W. Kerlin and M. Johnson. *Practical thermocouple thermometry*. Instrument Society of America, 1999.

ایجاد دمای مرجع برای ترموکوپل



Thermocouple with Ice Bath Reference



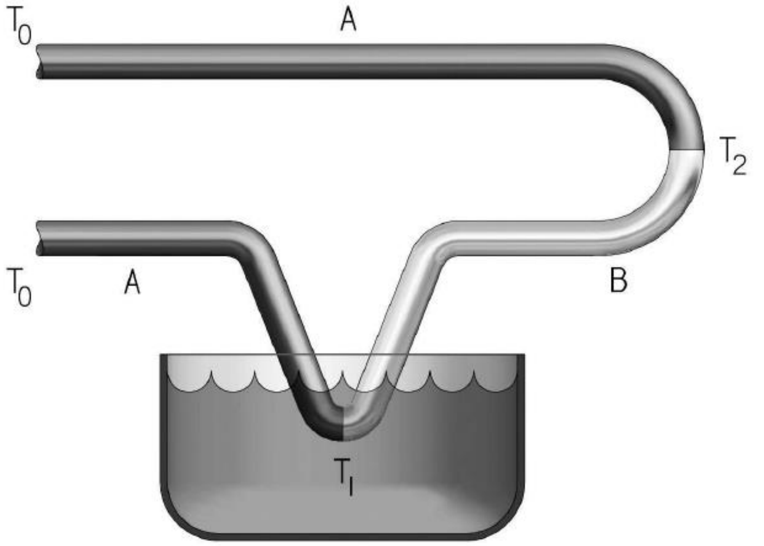
A Thermocouple with Identical Extension Wires

$$V = S_C(T_1 - T_0) + S_A(T_2 - T_1) + S_B(T_1 - T_2) + S_C(T_0 - T_1)$$

$$V = S_{AB}(T_2 - T_1)$$

T. W. Kerlin and M. Johnson. *Practical thermocouple thermometry*. Instrument Society of America, 1999.

ایجاد دمای مرجع برای ترموکوپل



An Alternate Ice Bath Reference

$$V = S_A(T_2 - T_0) + S_B(T_1 - T_2) + S_A(T_0 - T_1)$$

$$V = S_A(T_2 - T_1) + S_B(T_1 - T_2)$$

$$V = S_{AB}(T_2 - T_1)$$

$$°F = 1.8 \times °C + 32$$

$$°C = (°F - 32)/1.8$$

$$K = °C + 273.15$$

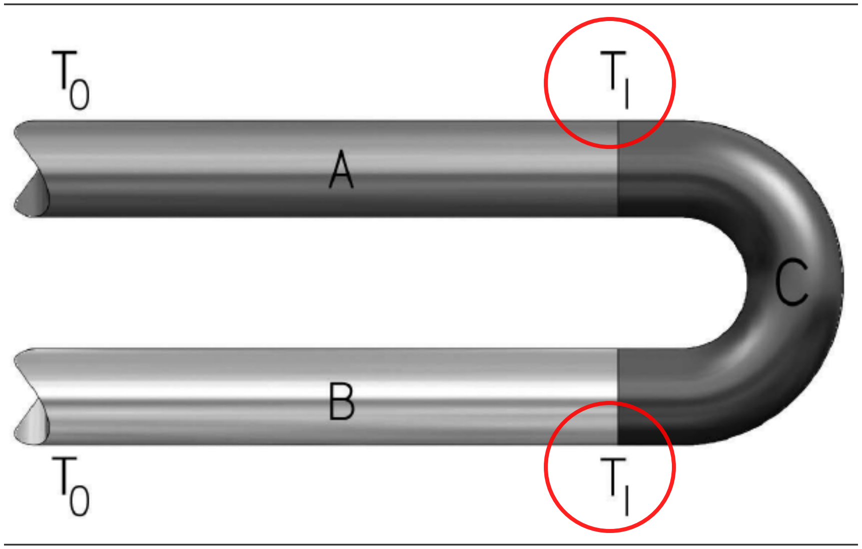
$$°R = °F + 459.67$$

Celsius and Fahrenheit scales are related to the Kelvin and Rankine absolute scales, respectively.

T. W. Kerlin and M. Johnson. *Practical thermocouple thermometry*. Instrument Society of America, 1999.

نحوه اتصال ترموکوپل

All of the depictions of thermocouples in previous sections have showed the two thermocouple wires joined at the junction, but there was no mention of *how* they were joined. Were they twisted together, welded, soldered, bolted, clamped—or what? *Thermoelectrically, it does not matter*!



A Thermocouple with a Third Material at the Junction

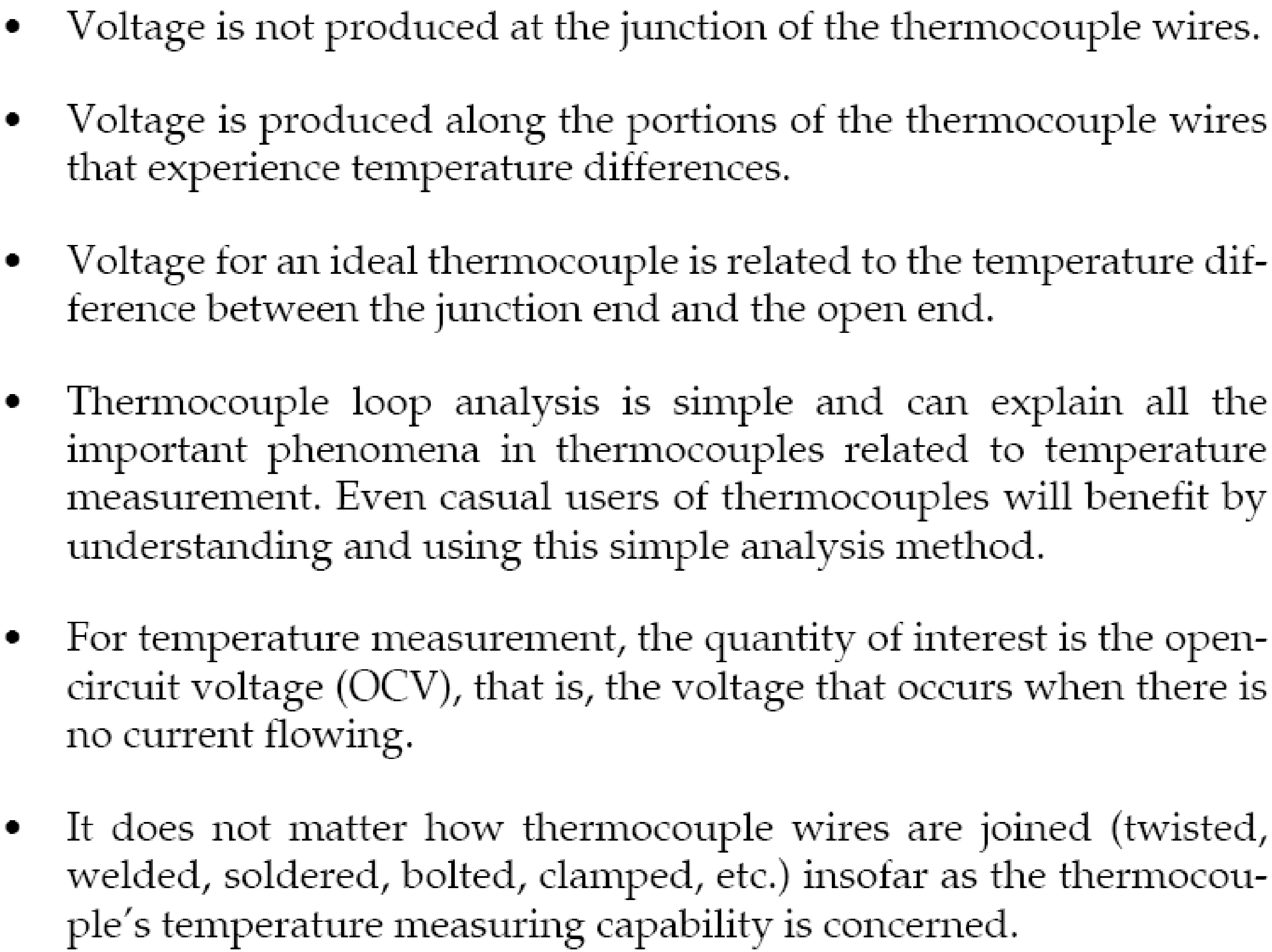
هم دمایی در هر دو سر مواد ترموالکتریک مهم است.

$$V = S_A(T_1 - T_0) + S_C(T_1 - T_1) + S_B(T_0 - T_1)$$

$$V = S_{AB}(T_1 - T_0)$$

T. W. Kerlin and M. Johnson. *Practical thermocouple thermometry*. Instrument Society of America, 1999.

نکات مهم در اندازه گیری بوسیله ترموکوپل



- Voltage is not produced at the junction of the thermocouple wires.
- Voltage is produced along the portions of the thermocouple wires that experience temperature differences.
- Voltage for an ideal thermocouple is related to the temperature difference between the junction end and the open end.
- Thermocouple loop analysis is simple and can explain all the important phenomena in thermocouples related to temperature measurement. Even casual users of thermocouples will benefit by understanding and using this simple analysis method.
- For temperature measurement, the quantity of interest is the open-circuit voltage (OCV), that is, the voltage that occurs when there is no current flowing.
- It does not matter how thermocouple wires are joined (twisted, welded, soldered, bolted, clamped, etc.) insofar as the thermocouple's temperature measuring capability is concerned.

T. W. Kerlin and M. Johnson. *Practical thermocouple thermometry*. Instrument Society of America, 1999.

انواع ترموکوپل

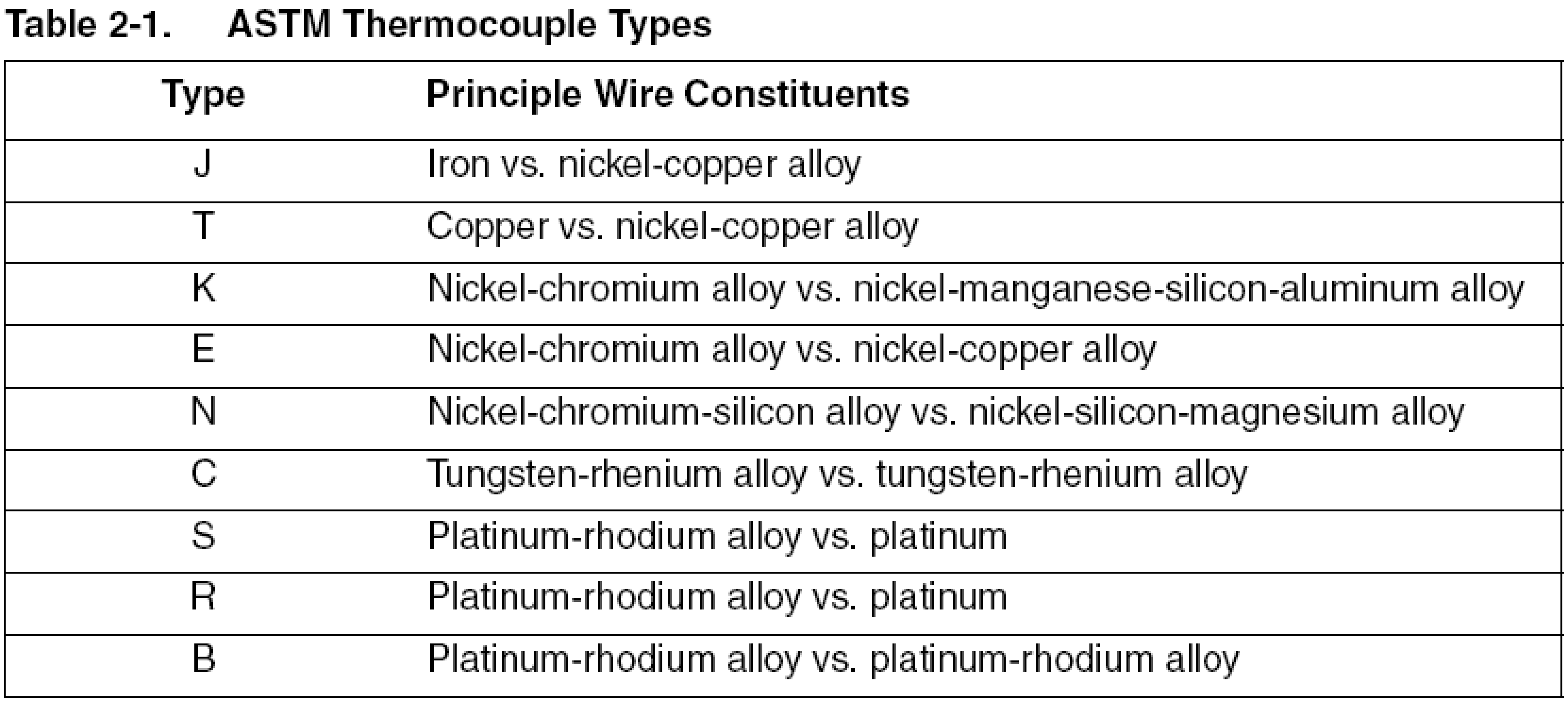


Table 2-1. ASTM Thermocouple Types

Type	Principle Wire Constituents
J	Iron vs. nickel-copper alloy
T	Copper vs. nickel-copper alloy
K	Nickel-chromium alloy vs. nickel-manganese-silicon-aluminum alloy
E	Nickel-chromium alloy vs. nickel-copper alloy
N	Nickel-chromium-silicon alloy vs. nickel-silicon-magnesium alloy
C	Tungsten-rhenium alloy vs. tungsten-rhenium alloy
S	Platinum-rhodium alloy vs. platinum
R	Platinum-rhodium alloy vs. platinum
B	Platinum-rhodium alloy vs. platinum-rhodium alloy

American Society for Testing and Materials (ASTM)

T. W. Kerlin and M. Johnson. *Practical thermocouple thermometry*. Instrument Society of America, 1999.

انواع ترموکوپل

The reference temperature of 0°C.

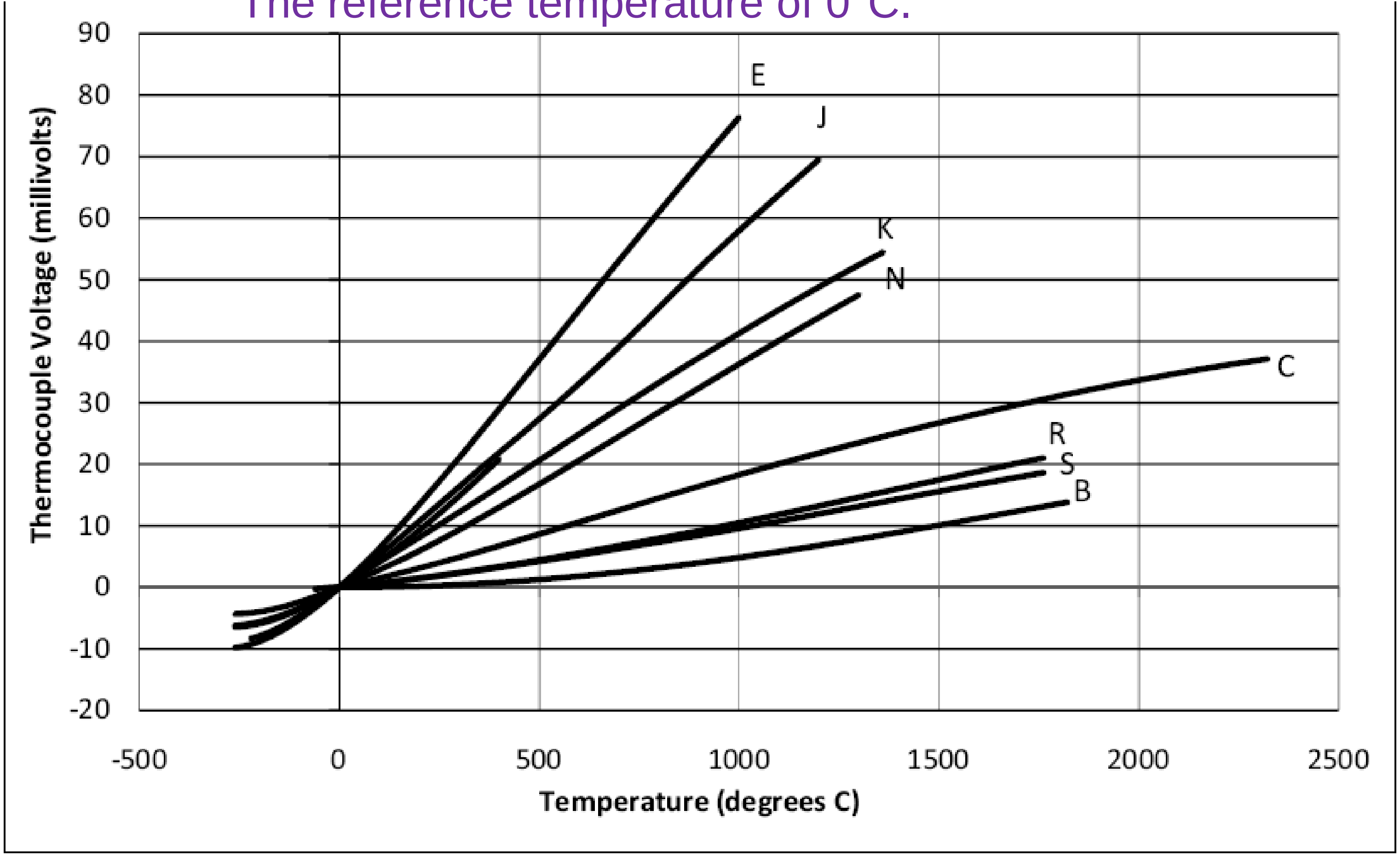
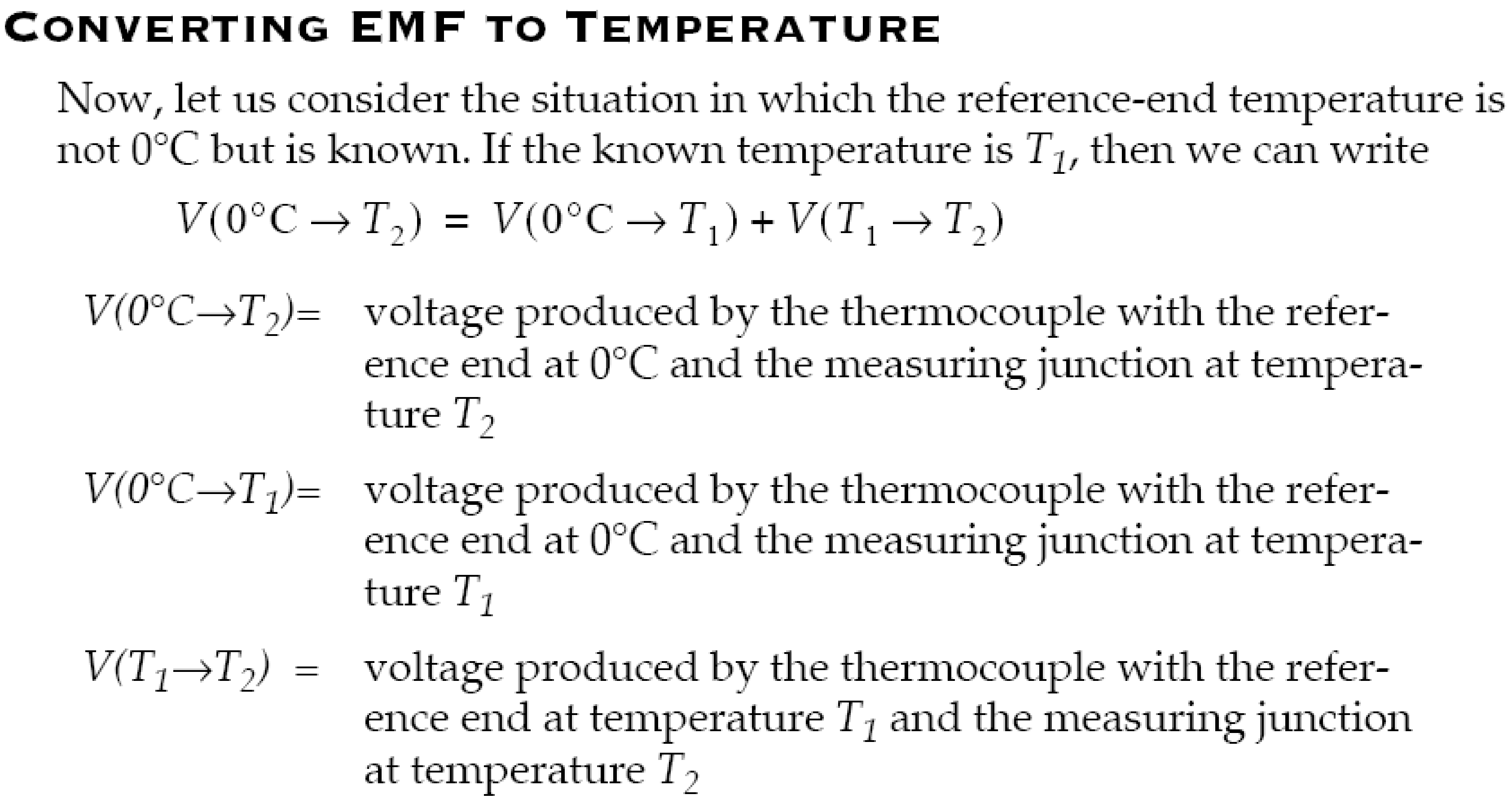


Figure 3-1. Thermoelectric EMFs for Standard Thermocouples

T. W. Kerlin and M. Johnson. *Practical thermocouple thermometry*. Instrument Society of America, 1999.



CONVERTING EMF TO TEMPERATURE

Now, let us consider the situation in which the reference-end temperature is not 0°C but is known. If the known temperature is T_1, then we can write

$$V(0°\mathrm{C} \rightarrow T_2) = V(0°\mathrm{C} \rightarrow T_1) + V(T_1 \rightarrow T_2)$$

$V(0°C \rightarrow T_2) =$	voltage produced by the thermocouple with the reference end at 0°C and the measuring junction at temperature T_2
$V(0°C \rightarrow T_1) =$	voltage produced by the thermocouple with the reference end at 0°C and the measuring junction at temperature T_1
$V(T_1 \rightarrow T_2) =$	voltage produced by the thermocouple with the reference end at temperature T_1 and the measuring junction at temperature T_2

T. W. Kerlin and M. Johnson. *Practical thermocouple thermometry*. Instrument Society of America, 1999.

اندازه گیری دما بوسیله ترموکوپل

EXAMPLE

A Type N thermocouple produces an emf of 10.610 mV when the open-end temperature is 20°C. What is the measuring-junction temperature?

SOLUTION

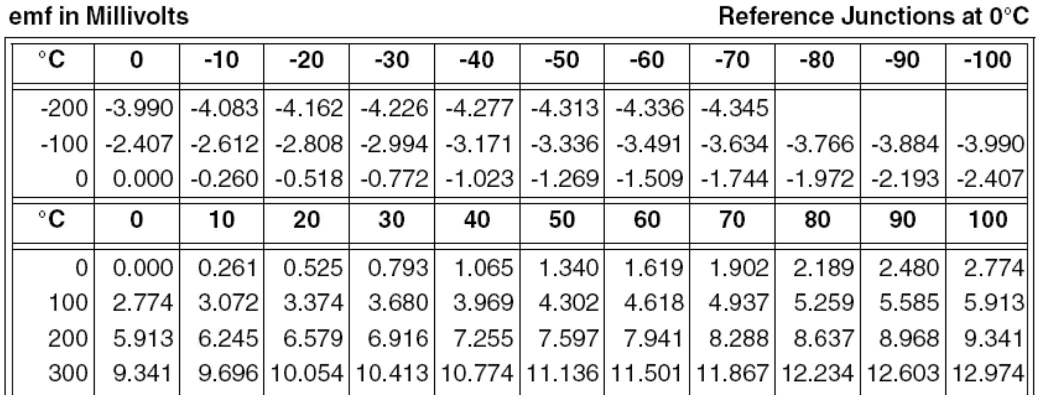
According to Appendix C, $V(0°C \rightarrow 20°C)$ is 0.525 mV.

Therefore,

$$V(0°C \rightarrow T_2) = 0.525 + 10.610 = 11.135\ mV$$

This is the emf that would have been measured if the reference temperature had been 0°C. Again, using Appendix C, we find that $T_2 = 350°C$.

TYPE N



emf in Millivolts

Reference Junctions at 0°C

°C	0	-10	-20	-30	-40	-50	-60	-70	-80	-90	-100
-200	-3.990	-4.083	-4.162	-4.226	-4.277	-4.313	-4.336	-4.345			
-100	-2.407	-2.612	-2.808	-2.994	-3.171	-3.336	-3.491	-3.634	-3.766	-3.884	-3.990
0	0.000	-0.260	-0.518	-0.772	-1.023	-1.269	-1.509	-1.744	-1.972	-2.193	-2.407
°C	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
0	0.000	0.261	0.525	0.793	1.065	1.340	1.619	1.902	2.189	2.480	2.774
100	2.774	3.072	3.374	3.680	3.969	4.302	4.618	4.937	5.259	5.585	5.913
200	5.913	6.245	6.579	6.916	7.255	7.597	7.941	8.288	8.637	8.968	9.341
300	9.341	9.696	10.054	10.413	10.774	11.136	11.501	11.867	12.234	12.603	12.974

T. W. Kerlin and M. Johnson. *Practical thermocouple thermometry*. Instrument Society of America, 1999.

اندازه گیری دما بوسیله ترموکوپل

EXAMPLE

A Type J thermocouple is connected to copper wires that connect to a readout instrument. What voltage is produced if the junction is at 400°C and the connection to copper is at 100°C?

SOLUTION

The copper section contributes no voltage because both conductors are identical. The Type J segment contributes the following voltage:

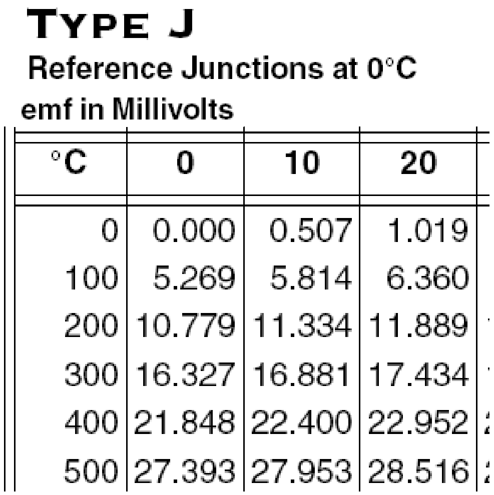
$$V = V(400^oC - 100^oC)$$

Using Equation 2-10 gives

$$V(400^oC - 100^oC) = V(400^oC - 0^oC) - V(100^oC - 0^oC)$$

That is, we can use the thermocouple tables (referenced to 0°C). Using the table in Appendix C for Type J thermocouple gives

$$V(400^oC - 100^oC) = 21.848 - 5.269 = 16.579\ mv$$



TYPE J

Reference Junctions at 0°C

emf in Millivolts

°C	0	10	20
0	0.000	0.507	1.019
100	5.269	5.814	6.360
200	10.779	11.334	11.889
300	16.327	16.881	17.434
400	21.848	22.400	22.952
500	27.393	27.953	28.516

T. W. Kerlin and M. Johnson. *Practical thermocouple thermometry*. Instrument Society of America, 1999.