Unit 15

Answers: Thermoelectric Effect

Quick checks

1 a In a loop of a single metal, whatever e.m.f. the temperature difference makes along one wire is matched exactly by an equal one along the other, in the opposite direction round the loop. A thermocouple needs **two different metals**.

2 b The Peltier effect is reversible: heat absorbed at a junction for a current one way is given out there for a current the other way. So the two sides swap. (Joule heating, which also takes place, warms both sides a little whichever way the current flows.)

3 a A temperature difference between the junctions of two different metals makes an e.m.f.: heat energy into electrical energy. (b is thermionic emission; c is Joule heating; d is the magnetic effect of a current.)

4 b Two different metals and two junctions at different temperatures: with no temperature difference, there is no e.m.f.

5 b The e.m.f. comes from the way the electrons' energies spread out with temperature, and how strongly each metal's electrons diffuse changes with temperature, so the e.m.f. per degree isn't constant (this change is the Thomson effect). Resistance affects the current, not the e.m.f.

6 c A thermocouple's e.m.f. depends on the temperature difference between its junctions, so with one junction at a known temperature it measures the other's.

7 b Thermocouples used for measuring are chosen so that, over their working range, the e.m.f. rises steadily with the temperature difference, far below their neutral temperature. (Iron–constantan, type J, reaches about 45 mV at 800 °C; at that temperature its iron wire oxidizes quickly, so type K is usually preferred above about 750 °C.)

8 b The Peltier effect is reversible: reversing the current makes the cold side hot and the hot side cold.

9 a Both matter. A larger temperature difference lets more of the heat become electrical energy (no heat engine can beat the Carnot limit, $1 - T_{cold}/T_{hot}$), and the materials decide how much of that limit is reached: a good thermoelectric material has a large Seebeck effect, conducts electricity well and conducts heat badly.

10 c Linear: $E \propto \Delta\theta$. $E = 5 \times \dfrac{500}{100} = 25$ mV.

11 b For a cooler, COP = heat taken from the cold side ÷ electrical power put in. So $Q_c = 0.5 \times 10 = 5$ W. (The hot side gives out 5 + 10 = 15 W.)

12 c The difference is 300 − 20 = 280 °C, at 0.1 mV/°C: $E = 280 \times 0.1 = 28$ mV. (A real copper–constantan couple gives about 13 mV for this difference; the question's 1 mV per 10 °C is a made-up value.)

12.

a. When two wires of different metals are joined into a loop and the two junctions are kept at different temperatures, an e.m.f. is set up and a current flows round the loop. This is the Seebeck effect; the e.m.f. is the thermo e.m.f.

b. Different metals have different electron densities. At each junction, free electrons diffuse from the metal of higher electron density to the other, setting up a contact potential. In a loop like Figure 15.2 with both junctions at the same temperature, the two contact potentials are equal and opposite and cancel. When one junction is heated, its electrons diffuse faster and its contact potential grows, so the two no longer cancel: the net e.m.f. drives a current, from copper to iron through the hot junction. (More exactly, the e.m.f. builds up along each wire, as its electrons diffuse from the hot end to the cold; the two metals differ in how much, and the difference is the thermo e.m.f.)

c. The nature of the two metals (their places in the thermoelectric series), and the temperatures of the two junctions (above all their difference).

d. $\dfrac{dE}{d\theta} = a + 2b\theta = 0$ at the neutral temperature:

$$\theta_n = -\frac{a}{2b} = -\frac{14}{2 \times (-0.04)} = \mathbf{175\ ^\circ C}$$

The e.m.f. changes sign where $E = \theta(a + b\theta) = 0$, other than at θ = 0:

$$\theta_i = -\frac{a}{b} = -\frac{14}{-0.04} = \mathbf{350\ ^\circ C}$$

13.

a. The e.m.f. set up in a thermocouple, a loop of two different metals, when its two junctions are at different temperatures.

b. **Origin:** the free electrons of the two metals diffuse differently: at each junction they diffuse from the metal of higher electron density to the other, setting up contact potentials that cancel when the junctions are at the same temperature but not when one is hotter (more exactly, the electrons diffuse from hot to cold along each wire, differently in the two metals). **Variation** (Figure 15.4): with the cold junction fixed, the e.m.f. is zero when the junctions are at the same temperature; as the hot junction is heated it rises, reaches a maximum at the neutral temperature θn, falls to zero at the temperature of inversion θi, and then reverses. The curve is a parabola, $E = \alpha\theta + \frac{1}{2}\beta\theta^2$, symmetric about θn, with $\theta_n = (\theta_c + \theta_i)/2$.

c. $\dfrac{dE}{d\theta} = 10^{-5} - 2 \times 0.01 \times 10^{-5}\,\theta = 0$, so

$$\theta_n = \frac{10^{-5}}{0.02 \times 10^{-5}} = \mathbf{50\ ^\circ C}$$

$$E_m = 10^{-5} \times 50 - 0.01 \times 10^{-5} \times 50^2 = 5 \times 10^{-4} - 2.5 \times 10^{-4} = 2.5 \times 10^{-4} = \mathbf{0.25\ mV}$$

14. a. When a current is passed through a thermocouple, heat is given out at one junction and absorbed at the other; reversing the current interchanges them (Figure 15.6). In the Seebeck effect a difference of temperature produces an e.m.f. and a current; in the Peltier effect a current, from an outside source, produces a difference of temperature.

b. In a copper–iron thermocouple, the Seebeck current flows from copper to iron at the hot junction. If a current is driven through the same couple in that direction, the Peltier effect **absorbs** heat at that junction and gives it out at the other: it tends to make the very temperature difference that would drive such a current. One effect turns a flow of heat into electrical energy, the other uses electrical energy to move heat, so each is the other run backwards.

c.

	Seebeck effect	Peltier effect
Cause	a temperature difference between the junctions	a current through the junctions
Result	an e.m.f. and a current	heat given out at one junction, absorbed at the other
Energy	heat → electrical energy	electrical energy → moving heat
Reverse it	reversing the temperatures reverses the current	reversing the current swaps hot and cold
Uses	thermocouple thermometers, thermopiles, thermoelectric generators (spacecraft, flame-failure valves)	thermoelectric coolers: portable fridges, cooling camera sensors and lasers

Both need two different conductors and are reversible, and both are strongest in semiconductors such as bismuth telluride.

d. $E = 25 \times 100 + 0.01 \times 100^2 = 2500 + 100 = 2600\ \mu = \mathbf{2.6\ mV}$

15.

a. The **neutral temperature** θn is the temperature of the hot junction at which the thermo e.m.f. is a maximum. The **temperature of inversion** θi is the temperature of the hot junction at which the e.m.f. becomes zero and then reverses. They are found by keeping the cold junction at a fixed temperature (in ice), heating the hot junction in an oil bath, and recording the e.m.f. (with a galvanometer or potentiometer) against its temperature: θn is where the curve peaks, θi where it crosses zero (Figure 15.4). If the coefficients are known, $\theta_n = -\alpha/\beta$ and $\theta_i = 2\theta_n - \theta_c$.

b. On the **nature of the two metals** and on the **temperature of the cold junction**: $\theta_i = 2\theta_n - \theta_c$.

c. $E = 16.3 \times 10^{-6} \times 100 + \frac{1}{2} \times (-0.042 \times 10^{-6}) \times 100^2$

$= 1.63 \times 10^{-3} - 0.21 \times 10^{-3} = \mathbf{1.42 \times 10^{-3}\ V}$ (1.42 mV)

16.

a. **Principle:** the Seebeck effect: two different metals joined at two junctions at different temperatures produce an e.m.f. that depends on the temperature difference. **Construction:** two wires of different metals or alloys (for example chromel and alumel), joined at one end by welding or twisting into a small bead, the **measuring (hot) junction**; their other ends are joined to copper leads at a **reference (cold) junction**, kept at a known temperature, and the leads go to a meter.

b. The e.m.f. is measured with a millivoltmeter or a potentiometer, and turned into a temperature with the couple's calibration table, knowing the reference junction's temperature (ice at 0 °C, or measured by a sensor in the meter, which then adds its share). **In industry** the probe, in a steel or ceramic sheath, is put into furnaces, kilns, boilers, engine exhausts, molten metal and ovens; its signal goes to a controller that switches the heating to hold the temperature. **Advantages:** very wide range (−200 °C to about 1700 °C), small and quick to respond, cheap and rugged, needs no power supply, its signal can be sent far and recorded. **Limitations:** the e.m.f. is small (microvolts per degree) and so easily disturbed by electrical noise; it is not exactly proportional to temperature, so tables are needed; the reference junction's temperature must be known; accuracy about ±1 to ±2 °C, less than a good resistance thermometer; wires can corrode or change with use at high temperatures.

c. $\theta_i = 2\theta_n - \theta_c = 2 \times 270 - 30 = \mathbf{510\ ^\circ C}$

17. a. **Chromel–alumel (type K)**, nickel alloys: a fairly large e.m.f. (about 41 μV/°C), nearly proportional to temperature, resists oxidation up to about 1250 °C; the general-purpose choice. **Iron–constantan (type J):** a larger e.m.f., cheap, but its iron rusts, so up to about 750 °C. **Copper–constantan (type T):** stable and accurate at low temperatures, down to −200 °C. **Platinum against platinum–rhodium (types R, S):** a small e.m.f., but very stable and resistant to heat and chemicals, up to about 1600 °C, for furnaces and as standards. **Antimony–bismuth** (the ends of the thermoelectric series), the largest e.m.f. of the pure metals, in thermopiles. In general a pair is chosen for a large e.m.f. per degree, an e.m.f. that changes steadily (neutral temperature well above the working range), stability over time, and wires that survive the heat and the surroundings.

b. The average Seebeck coefficient is the e.m.f. per degree of difference:

$$S = \frac{E}{\theta_h - \theta_c} = \frac{2.8}{150 - 30} = \frac{2.8}{120} = \mathbf{0.0233\ mV/^\circ C}$$

18. a. A thermopile (Figure 15.8) is many antimony–bismuth thermocouples joined in series. One set of junctions is blackened with lamp black and faces the radiation; the other set is shielded and stays cool. Radiation falling on the blackened junctions is absorbed and warms them, so every thermocouple has a temperature difference and an e.m.f.; in series, the e.m.f.s add. A galvanometer across the ends deflects, and the more intense the radiation, the larger the deflection. So a thermopile detects heat radiation and measures its intensity, from the Sun, a furnace or, in a modern infrared thermometer, a person's forehead.

b. Taking the cold junction at 0 °C, E ∝ θ:

$$E = 5 \times \frac{150}{200} = \mathbf{3.75\ mV}$$

(If the cold junction were at some other temperature θc, the e.m.f. would be proportional to θ − θc instead, and the answer would be different.)

19. a. **Construction:** two wires of different metals joined at the measuring junction (welded into a small bead), their other ends joined to copper wires at the **reference junction**, which is kept at a standard temperature, usually 0 °C in a flask of melting ice and water; the copper wires go to a potentiometer or millivoltmeter. **Calibration:** with the reference junction at 0 °C, the measuring junction is put in turn at **fixed points**, temperatures that can be reproduced exactly (melting ice 0 °C, boiling water 100 °C at standard pressure, freezing tin 231.9 °C, freezing zinc 419.5 °C and so on), or beside a standard thermometer in a bath; the e.m.f. at each is recorded, and a calibration curve or table (or the coefficients of a formula such as $E = \alpha\theta + \frac{1}{2}\beta\theta^2$) is drawn up. Afterwards, the e.m.f. measured at any temperature gives the temperature from the table. Meters without ice measure the temperature of their own terminals and correct for it (**cold-junction compensation**).

b. $S = \frac{E}{\Delta\theta} = \frac{4.5}{100} = \mathbf{0.045\ mV/^\circ C}$ (45 μV/°C)