Unit 15 · Thermoelectric Effect

STUDY NOTES

WHAT NEB'S GRADE 12 EXAM ASKS

- **CDC's grid (2078):** Electricity and Magnetism (Units 14–19 together): 21 of 75 marks
- **The paper:** 11 MCQs × 1 · 8 short × 5 · 3 long × 8; 3 hours; 1 mark per expected point
- **CDC's model paper:** MCQ: the cold junction is cooled; the neutral temperature **stays the same**
- **MCQ (1 mark)**
  - define the Seebeck effect
  - what makes the thermo e.m.f.
  - why the curve isn't straight
  - a thermocouple's main use
  - furnace: e.m.f. rises with the difference
  - Peltier current reversed
  - a generator's efficiency
  - linear e.m.f. from a ratio
  - Peltier COP: heat taken in
- **Short and long (5 or 8 marks, in parts)**
  - define Seebeck effect, thermo e.m.f., neutral temperature, temperature of inversion
  - cause of thermo e.m.f., with a diagram; what it depends on
  - variation with the hot junction's temperature: the graph
  - Peltier effect, its cause; converse of Seebeck; compare the two
  - thermocouple: principle, construction, measuring temperature, materials, calibration, advantages and limits
  - thermopile: construction and working
  - numericals: θ_n, θ_i, $E_{\max}$ from the coefficients; θ_i from θ_n and θ_c; Seebeck coefficient

Key terms

Thermoelectric effect: an e.m.f. from a temperature difference across a material or across the junctions of two materials; its electricity is **thermoelectricity**.

Seebeck effect (1821): a loop of two different metals with its junctions at **different temperatures** sets up a small e.m.f. (**thermo e.m.f.**) and a current (**thermoelectric current**).

Thermocouple: two different metals joined in a loop to produce thermoelectricity.

Thermoelectric series: metals in an order that gives the current's direction and roughly the e.m.f.'s size for any pair.

Neutral temperature θ_n: hot junction's temperature at which the thermo e.m.f. is a **maximum**.

Temperature of inversion θ_i: hot junction's temperature at which the e.m.f. is **zero and then reverses**.

Peltier effect (1834): current through a thermocouple: heat **given out** at one junction, **absorbed** at the other; reverse of Seebeck.

Thomson effect (1851): current along **one conductor** whose ends are at different temperatures: heat given out or absorbed along it.

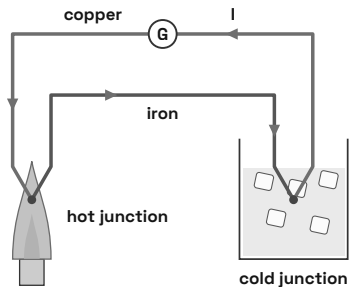
Thermopile: many Sb–Bi thermocouples in series; detects and measures heat radiation.

Seebeck coefficient: e.m.f. per degree of difference, $E/\Delta\theta$.

Formulas

$E = \alpha\theta + \frac{1}{2}\beta\theta^2$	cold junction 0 °C; α, β thermoelectric coefficients **Use:** thermo e.m.f.
$\theta_n = -\frac{\alpha}{\beta}$	from $dE/d\theta = 0$ **Use:** neutral temperature
$\theta_i = -\frac{2\alpha}{\beta} = 2\theta_n$	cold junction 0 °C **Use:** inversion
$\theta_n = \frac{\theta_c + \theta_i}{2}$	cold junction at θ_c **Use:** inversion: $\theta_i = 2\theta_n - \theta_c$
$E = a\theta + b\theta^2$	$b = \frac{1}{2}\beta$ **Use:** $\theta_n = -\frac{a}{2b}$, $\theta_i = -\frac{a}{b}$
$S = \frac{E}{\theta_h - \theta_c}$	μV/°C **Use:** average Seebeck coefficient

Seebeck effect



Copper–iron thermocouple: hot junction in a flame, cold junction in ice; the current flows from copper to iron at the hot junction, iron to copper at the cold.

- e.m.f. small: Cu–Fe, ice and boiling water about 1 mV; type K (chromel–alumel) about 41 μV/°C
- one metal only (two copper wires): **no** current, however hot

Cause (contact potential, the books' account)

1. different metals, different free-electron densities
2. electrons diffuse from higher to lower density → a **contact potential** at each junction
3. junctions at one temperature: the two contact potentials equal and opposite → no current
4. one junction heated: faster diffusion, larger contact potential there → net e.m.f.

- really: the e.m.f. is made **along each wire** where it has a temperature gradient (thermal diffusion of electrons); two metals give different voltages, which don't cancel; the junctions only mark where the metal changes

Thermo e.m.f. depends on

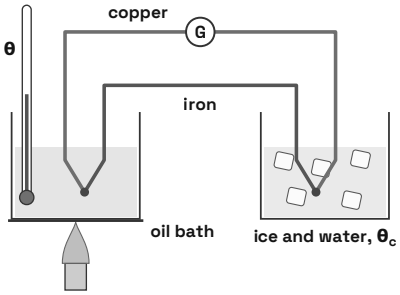
- the **pair of metals** (places in the series)
- the **temperatures of the junctions** (their difference)

Thermoelectric series

Sb, Fe, Zn, Ag, Au, Sn, Pb, Cu, Pt, Co, Ni, Bi

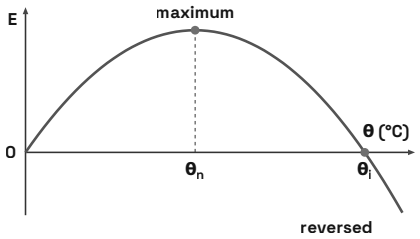
- current through the **cold** junction: from the **earlier** metal to the later (through the hot junction, later to earlier)
- farther apart in the series → larger e.m.f. (small differences); **Sb–Bi** the strongest pair
- **"hot coffee"**: at the hot junction, Cu → Fe
- **"ABC"**: Antimony → Bismuth at the Cold junction
- heating and cooling swapped → current reverses

E.m.f. against temperature



Cu–Fe thermocouple: cold junction in ice and water at θ_c, hot junction beside a thermometer in an oil bath; a galvanometer shows the current.

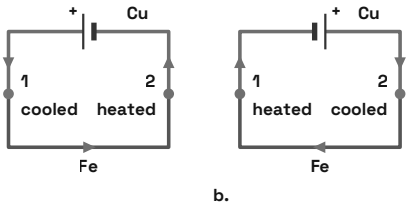
- oil bath, not water: heated well above 100 °C
- both junctions at θ_c: no e.m.f.; as the hot junction warms: e.m.f. **rises**, reaches a **maximum** at θ_n, **falls** to zero at θ_i, then **reverses**



A parabola, symmetric about θ_n: maximum at θ_n, zero at $\theta_i = 2\,\theta_n$ (cold junction at 0 °C), then negative.

- Cu–Fe: θ_n about **270 °C**; α positive, β **negative** (the parabola turns over)
- θ_n depends **only on the two metals**, not on the cold junction (slope $\alpha + \beta\theta$ unchanged)
- θ_i depends on the metals **and** the cold junction: θ_c up → θ_i down by the same amount
- θ_n is halfway between θ_c and θ_i
- e.g. $\theta_n = 270$ °C, $\theta_c = 30$ °C → $\theta_i = 540 - 30 = 510$ °C
- e.g. $a = 14$ μV/°C, $b = -0.04$ μV/°C^2 → $\theta_n = 175$ °C, $\theta_i = 350$ °C
- curve bends because of the **Thomson effect**

Peltier effect



Cu–Fe couple and a cell: current Cu → Fe at junction 1 cools it, junction 2 warms; reversed, they swap.

- **reversible**: current reversed → hot and cold junctions swap
- unlike Joule heat: I^2Rt heats whatever the direction, $\propto I^2$; Peltier heat $\propto I$, changes sign with it

- Cu–Fe: heat **absorbed** where current goes Cu → Fe; **given out** where Fe → Cu
- fits Seebeck: a thermocouple's own current cools its hot junction, warms its cold one (heat → electrical energy)

Cause: iron at the higher contact potential

- current from higher to lower potential (Fe → Cu): charges lose energy → heat out, junction **hot**
- lower to higher (Cu → Fe): charges gain energy from the junction → junction **cool**

Uses: thermoelectric coolers: car and picnic fridges, cooling camera sensors, lasers, medical samples, water dispensers; reversed, a heater; no moving parts or refrigerant, silent, long-lasting, but more electricity than a compressor fridge

- COP 0.5, 10 W in → 5 W of heat taken in

	Seebeck	Peltier
cause	temperature difference	current
result	e.m.f., current	one junction hot, one cold
use	thermometers, thermopiles, generators	coolers, heaters

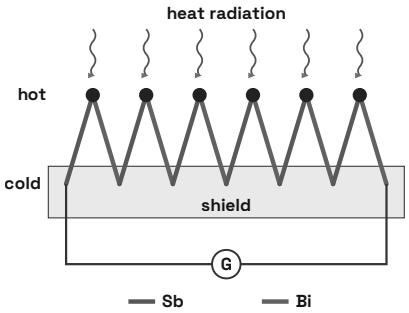
Thomson effect

- predicted by William Thomson (Lord Kelvin) from thermodynamics, then found
- one conductor, ends at different temperatures, a current: heat out or in along it; reversible
- **positive** (Cu, Ag, Zn, Sb): current hot → cold gives out heat
- **negative** (Fe, Co, Ni, Pt, Bi): current hot → cold absorbs heat
- **lead**: almost none → the reference metal

Thermocouples in use

- **construction**: two metal wires welded or twisted into a bead (measuring, hot junction); other ends joined to copper leads at a **reference (cold) junction** at a known temperature (0 °C in melting ice), leads to a millivoltmeter or potentiometer
- **calibration**: measuring junction at **fixed points** (ice 0 °C, boiling water 100 °C, freezing tin 231.9 °C, zinc 419.5 °C) or beside a standard thermometer; table or curve of e.m.f. against temperature
- **industry**: sheathed probes in furnaces, kilns, boilers, exhausts, molten metal; signal to a controller
- **advantages**: very wide range (−200 °C to about 1700 °C), small, quick, cheap, rugged, no power supply, signal sent far
- **limits**: small e.m.f., easily disturbed by noise; not proportional, needs tables; reference temperature must be known
- **types**: K chromel–alumel (to about 1250 °C, everyday), J iron–constantan (to about 750 °C), T copper–constantan (low temperatures), R and S platinum against platinum–rhodium (to about 1600 °C, very stable)
- a pair is chosen for: large e.m.f. per degree, steady change (θ_n well above the range), stability, wires that survive
- gas heaters: the flame's thermocouple holds the gas valve open
- **generators** (Seebeck): Voyager, Curiosity (heat of plutonium-238); wood-stove modules; a few % to about 8% efficient; depends on the materials and the temperature difference

Thermopile



Sb–Bi thermocouples in series in a zigzag; one set of junctions blackened, facing the radiation; the other shielded; a galvanometer across the ends.

- works on the **Seebeck effect**
- blackened (lamp black) junctions absorb radiation, warm up; every couple's e.m.f. adds in series (n couples, $n \times$ one)
- more intense radiation → larger deflection; Sun's radiation, furnaces; infrared forehead thermometers
- Sb and Bi: the two ends of the series → largest e.m.f. per degree

COMMON MISTAKES

✗ θ_n changes with the cold junction
✓ only θ_i does; θ_n depends on the metals alone.

✗ $\theta_i = 2\theta_n$ always
✓ only with the cold junction at 0 °C; else $\theta_i = 2\theta_n - \theta_c$.

✗ $\theta_n = -a/b$ for $E = a\theta + b\theta^2$
✓ $-a/2b$; $-\alpha/\beta$ is for the ½β form.

✗ β positive for Cu–Fe
✓ **negative**, or no maximum and no inversion.

✗ Peltier heat is Joule heat
✓ Peltier changes sign with the current; Joule heat doesn't.

✗ one metal heated at one end gives a Seebeck current
✓ a loop of one metal: no current.