Unit 17

Answers: Magnetic Properties of Materials

Quick checks

1 b **That the Earth is a great magnet**, in his book *De Magnete*. Oersted found the magnetic effect of a current (1820), Peregrinus described the two poles (1269), and Pierre Curie the temperature at which a magnet loses its magnetism (1895).

2 a $\chi = I/H = 300/(6 \times 10^5) = 5 \times 10^{-4}$, a number with no unit (the A/m cancel). Small and positive: a paramagnetic material.

3 a μr is slightly **less** than 1, so $\chi = \mu r - 1 = -2 \times 10^{-5}$: small and negative, **diamagnetic**. (A superconductor has $\mu r = 0$.)

4 c Each domain is **magnetized to saturation** all the time; with no field, the domains point **different ways** and their moments cancel. A field makes the nail a magnet by growing and turning the domains, not by magnetizing them.

5 b The core goes round its loop 50 times a second, losing the loop's area of energy (per unit volume) each time: it needs a **narrow loop of small area**, low coercivity, as soft iron and silicon steel have.

6 d $B = B_H/\cos\delta = 20/\cos 60^\circ = 20/0.5 = 40\ \mu$.

7 c Only a **ferromagnetic** substance keeps its magnetism after the field is removed. But not every ferromagnetic substance makes a good permanent magnet: soft iron is ferromagnetic, yet its coercivity is so low that it loses its magnetism easily. Permanent magnets are made from hard ferromagnetic materials such as steel and alnico.

8 b $B = B_H/\cos\delta = B_0/\cos 45^\circ = B_0/(1/\sqrt{2}) = \sqrt{2}\,B_0$.

9 b At a magnetic pole the dip is 90°, so $B_H = B\cos 90^\circ = 0$: the field there is vertical. At the magnetic equator the field is all horizontal.

10 d The force on a moving charge is $F = Bqv\sin\theta$ (Unit 16): zero on a charge at rest and on one moving along the field ($\theta = 0$), but not zero on one moving at an angle to it.

11 b Heat jiggles the atoms and disturbs their lining up, so the susceptibility **decreases** as the temperature rises; above the Curie temperature the substance is only paramagnetic, $\chi = C/(T - T_C)$.

12 a A diamagnetic substance is magnetized feebly **against** the field, so $\chi = I/H$ is **small and negative**, about -10^{-5}.
Some books print this question with the options isobaric, isogonic, isoclinic and isodynamic: those are names of lines on maps, not values of susceptibility, so none of them answers it. It is asked here with options that do.

13 **a** Magnetic lines of force **never intersect**: the field at a point has only one direction, and two lines crossing would give it two. (At a neutral point the field is zero, so there is no line through it at all.)

14 **c** The **Curie temperature**, after Pierre Curie: 770 °C for iron.

15 **a** The field is made by currents in the moving molten iron of the Earth's **outer core** (the geodynamo). There can be no permanent magnet at the center: it is far above iron's Curie temperature.

16 **a** $\tau = MB_H \sin\theta = 2 \times 0.4 \times 10^{-4} \times \sin 30^\circ = 0.4 \times 10^{-4}$ N m (Example 17.8).

17 **a** The loop's width along the H axis is twice the coercivity (from −Oc to +Of), so a smaller coercivity gives a **narrower** loop. The saturation magnetization sets its height, not its width.

18 **a** The generator's **permanent magnets** need a high coercivity and retentivity: the wide loop **a**. Transformer cores and electromagnet cores are magnetized and demagnetized again and again, so they need a low coercivity and a small loop area: the narrow loop **b**.
Some books print this question with options that leave out which loop goes with which use, so none of them can be chosen. It is asked here with complete options.

13.

a. A ferromagnet is magnetic because its atomic magnets line up together in **domains**, held in line by the strong exchange interaction between neighbors. Heat makes the atoms jiggle, which works against the lining up. Above the Curie temperature the jiggling wins: the atomic magnets point every way, the domains break up, and only a weak lining up remains when a field is applied, as in a paramagnet. So the substance becomes **paramagnetic**, with $\chi = C/(T - T_C)$. Cooled below the Curie temperature, the domains form again.

b. H = 1000 A/m, $\chi = 1272$.

$$B = \mu_0(1+\chi)H = 4\pi \times 10^{-7} \times 1273 \times 1000 = \mathbf{1.6\ T}$$

14. a. The **relative permeability** μr of a material is the ratio of its permeability to the permeability of a vacuum, $\mu_r = \mu/\mu_0$, where μ = B/H: how many times larger B is in the material than in a vacuum for the same H. It has no unit. The **magnetic susceptibility** χ is the ratio of the intensity of magnetization to the magnetizing field, $\chi = I/H$: how easily the material is magnetized. It has no unit.

b. The induction in a material is $B = \mu_0(H + I)$. Since $I = \chi H$,

$$B = \mu_0(H + \chi H) = \mu_0 H(1 + \chi)$$

Dividing by H, $\mu = B/H = \mu_0(1 + \chi)$, and dividing by μ_0,

$$\mu_r = 1 + \chi$$

c. It should be **ferromagnetic**, with a **high coercivity**, so that stray fields, knocks and handling don't demagnetize it, and a **high retentivity**, so that it stays strongly magnetized: a wide hysteresis loop, like that of steel or alnico. A **high Curie temperature** helps too, so that it keeps its magnetism when warm.

15. a. **Retentivity** is the magnetic induction left in a material when the magnetizing field is reduced to zero (Ob in Figure 17.13). **Coercivity** is the reverse magnetizing field needed to bring the magnetic induction in the material to zero (Oc).

b. i. **b**: its loop is narrow, so a very small reverse field brings B to zero. Soft iron has a **low coercivity**, and its loop has a small area.

ii. **b for the transformer core**: the core is taken round its loop 50 times a second, and the narrow loop's small area means little energy lost as heat, while its low coercivity lets it follow the changing field easily. **a for the permanent magnet**: its high coercivity means it is hard to demagnetize, and it keeps a large B when the field is removed. Its large loop area does not matter, since a permanent magnet is not taken round its loop.

iii. The area of the loop is the **energy lost (as heat) per unit volume of the material in one cycle of magnetization**, the hysteresis loss.

16. a. i. **Magnetic hysteresis** is the lagging of the magnetic induction B behind the magnetizing field H when H is taken through a cycle. The loop is drawn as in Figure 17.13: B against H, the first magnetization curve O to a (saturation), then a → b (H = 0, B = Ob, the retentivity) → c (B = 0, H = −Oc, the coercivity) → d (saturation the other way) → e → f → a.

ii. 1. **Retentivity** (Ob) shows how much magnetism the material keeps when the field is removed. 2. **Coercivity** (Oc) shows how large a reverse field is needed to demagnetize it: how firmly it holds its magnetism. 3. **Hysteresis loss**, the area of the loop, is the energy wasted as heat in each unit volume in every cycle of magnetization.

iii. A **permanent magnet** needs a high retentivity and, above all, a high coercivity, so that it stays magnetized: a wide loop (steel, alnico, neodymium–iron–boron). Its loss doesn't matter, since it isn't cycled. A **transformer core** is cycled 50 times a second, so it needs a small loop area (little heat) and a low coercivity, with a high permeability: a narrow loop (soft iron, silicon steel).

b. i.

	Diamagnetic	Paramagnetic	Ferromagnetic
1. Susceptibility	small and negative (about -10^{-5})	small and positive (about 10^{-5} to 10^{-3})	large and positive (hundreds to thousands)
2. In a field	magnetized feebly against the field; weakly repelled, moves towards weaker field; a rod sets across the field	magnetized feebly along the field; weakly attracted, moves towards stronger field; a rod sets along the field	magnetized strongly along the field; strongly attracted; keeps some magnetism when the field is removed
3. Examples	bismuth, copper, water	aluminium, platinum, oxygen	iron, cobalt, nickel

ii. A ferromagnet is made of **domains**, each magnetized to saturation. When it is magnetized, the domain walls move and the domains turn; but the walls catch on impurities and flaws in the crystal and jump past them, so the changes are not reversible. When the field is reduced, the walls do not all move back, and some magnetization remains (retentivity); a reverse field is needed to undo it (coercivity). So B on the way down differs from B on the way up: a loop. Diamagnetic and paramagnetic materials **have no domains**: each atom responds to the field by itself, at once, and the response disappears completely when the field is removed. Their

magnetization is always proportional to H, a single straight line through the origin, with no loop.