Lecture Notes
ELEC A6

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Magnetic circuit

Magnetic Field Concepts

<u>Magnetic Fields:</u>

- **Magnetic fields are the fundamental mechanism by which energy is converted (or transferred) from one form to another in motors, generators and transformers.**

Machines basic requirements

1) Presence of a “magnetic field” which can be produced by:

- **Use of permanent magnets**
- **Use of electromagnets**

Then one of the following is needed:

2) Motion to produce electric current (Generator)

3) Electric Current to produce motion (Motor)

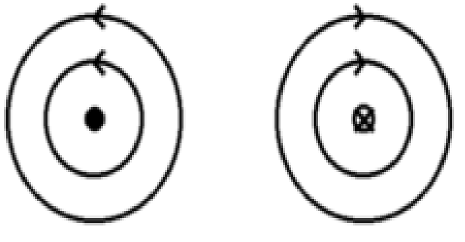
Ampere's Law

- **Any current carrying wire will produce a magnetic field around itself.**

Magnetic field around a wire:

<u>Ampere's Right-Hand-Rule</u>

- Thumb:Points in the direction of the current flow.
- Fingers: Wrapped around the conductor indicate the flux / magnetic field direction.

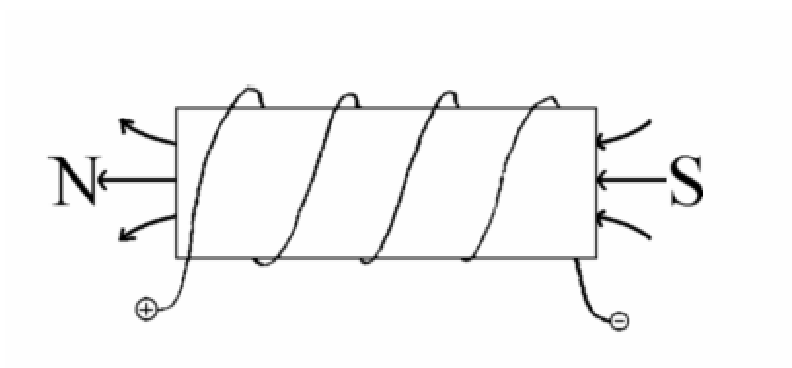


Ampere’s Law

Magnetic field around a coil:

<u>Ampere's Right-Hand-Rule</u>

- Fingers: wrapped in the direction of the coil indicate the current flow.
- Thumb: indicates the magnetic field (flux) direction



Basic Definitions

- **Magnetic Flux**
  - Symbol: ϕ
  - Unit: Weber (Wb)
- **Magnetic Flux Density**
  - Symbol: B
  - Unit: Tesla (T), 1 Tesla = 1 Wb/m^2
- $B = \phi/A$ where *A* is the cross-sectional area in m^2 through which the flux passes.
- **Magnetomotive Force (mmf)**
  - Symbol: $\mathfrak{I}$
  - Unit: Ampere-turns (At)
  - $\mathfrak{I} = N\,I$

Basic Definitions

- **Permeability**
  - Symbol: μ
  - Unit: Wb/At·m

- Permeability - a measure of the ease with which a magnetic field can be established in a given material.

- The value of μ varies depending on the type of material. The permeability of a vacuum (free-space): $\mu_0 = 4\pi \times 10^{-7}$

- For other materials: $\mu = \mu_0 \mu_r$

where μ_r is the relative permeability.

Basic Definitions

- **Reluctance**
  - Symbol: $\Re$
  - Unit: At/Wb
- Reluctance, $\Re$ (which is similar to resistance), is the opposition to the establishment of a magnetic field.

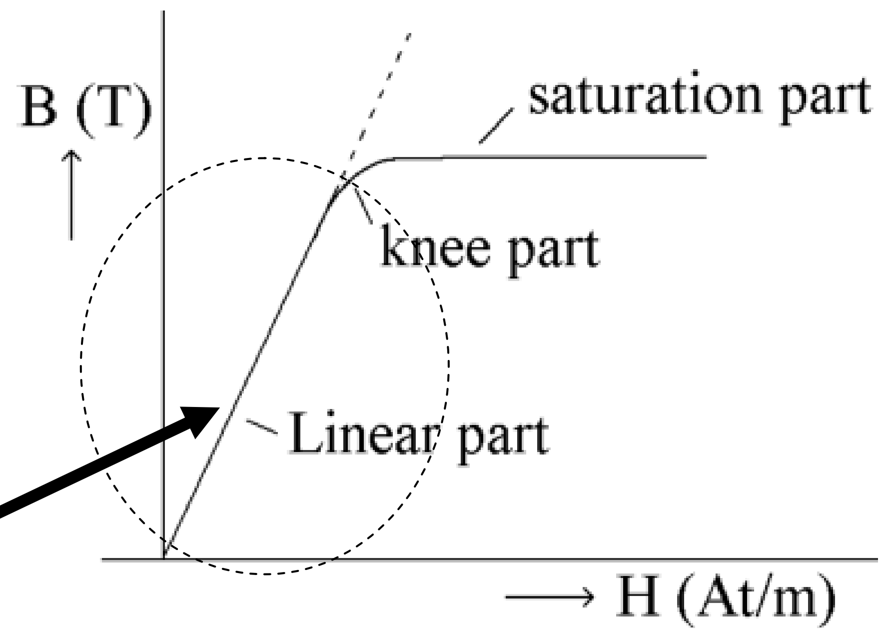
$$\Re = \frac{mmf}{flux} = \frac{NI}{\phi} = \frac{l}{\mu A}$$

- L - length of the magnetic path
- *A* - cross-sectional area for the flux path.

Basic Definitions

- Magnetic field intensity, or the magnetizing force is defined as the mmf per unit length, H.
- $$H = \frac{NI}{l} = \frac{B}{\mu}$$

Only in the linear region

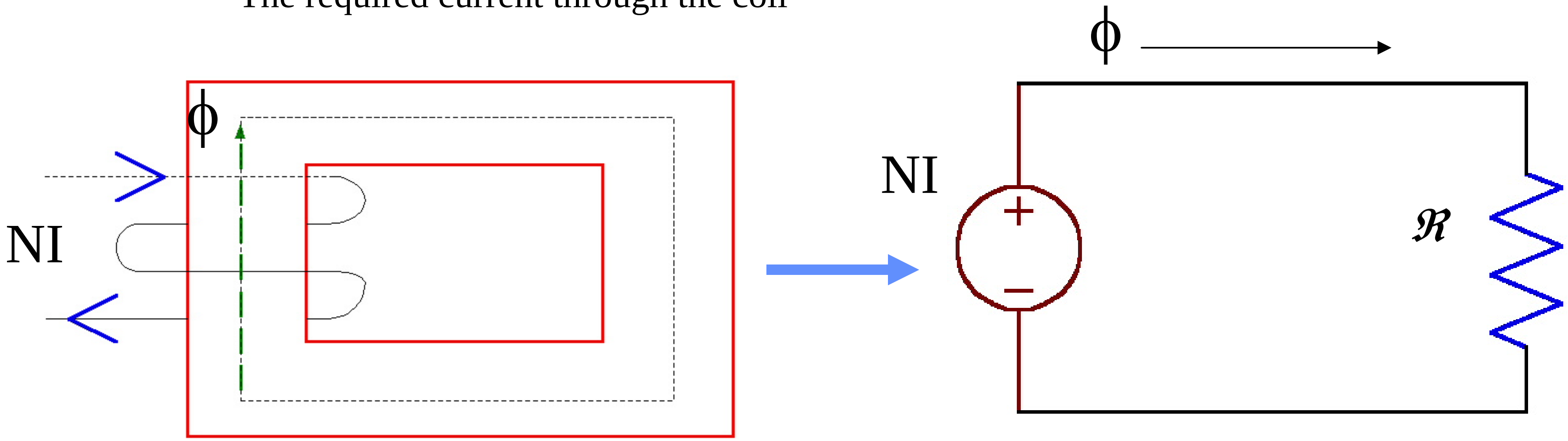


Basic Definitions

Electric Circuit	Magnetic Circuit
Voltage, V (emf) [V]	**mmf, $\Im$ [At]**
Current, I [A]	**Magnetic flux, ϕ [Wb]**
Resistance, R, [Ω]	**Reluctance, R [At/Wb]**
$R = \frac{V}{I}$	$\Re = \frac{\Im}{\phi}$

Examples

- **Example 1:** For A = 16 cm2, l = 40 cm, number of turns = 350 and μ_r = 50,000, to get a magnetic flux density = 1.5 T, find:
  - The flux
  - The required current through the coil



Examples

$$(a)\ \phi = B * A = 1.5 * 16 * 10^{-4} = 2.4\, mWB$$

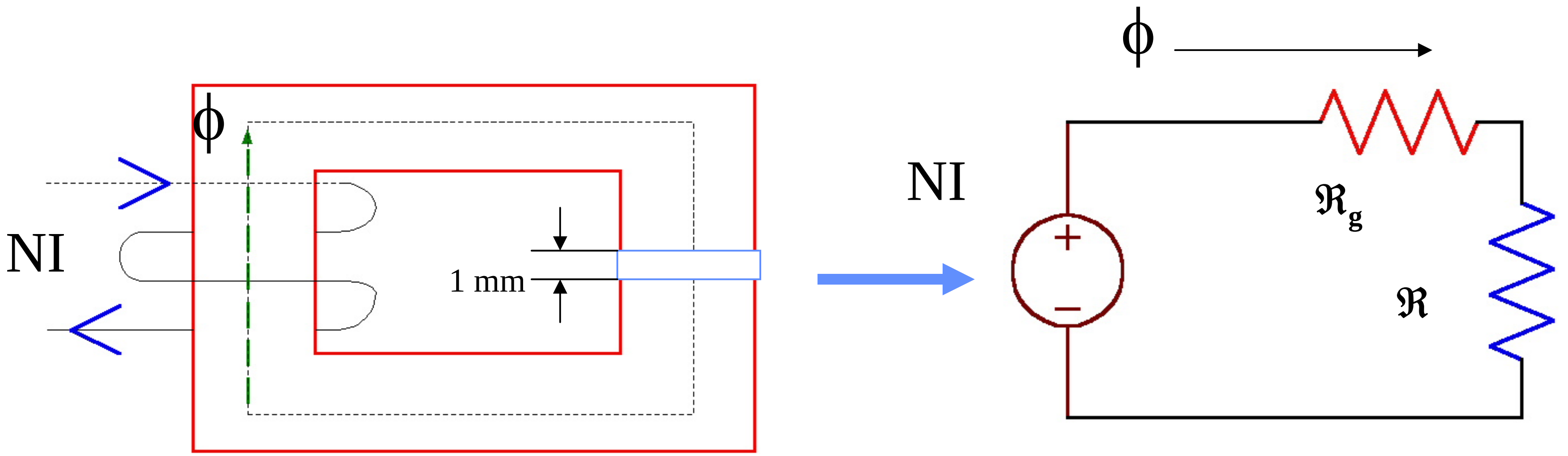
$$(b)\ \Re = \frac{L}{\mu_r \mu_o A} = \frac{40 * 10^{-2}}{50{,}000 * 4 * \pi * 10^{-7} * 16 * 10^{-4}} = 3979 \text{ A.t/WB}$$

$$\text{but } \Im = \Re * \phi$$

$$\text{so, } NI = \Re * \phi \Rightarrow I = \frac{\Re * \phi}{N} = 27.3 \text{ mA}$$

Examples

- **Example 2:** If an air gap, as shown, is inserted in the magnetic circuit mentioned in example 1, find:
  - The flux
  - The required current through the coil



Examples

(a) *T*he flux will not change from the previous example because B is kept the same as well as the magentic circuit cross sectional area

(b) Two reluctances need to be calculated, the one due to the magnetic circuit ($\Re$) and the one due to the air gap ($\Re_g$)

$$\Re = \frac{L}{\mu_r \mu_o A} = \frac{40*10^{-2}}{50{,}000*4*\pi*10^{-7}*16*10^{-4}} = 3979 \text{ A.t/WB}$$

$$\Re_g = \frac{L}{\mu_r \mu_o A} = \frac{1*10^{-3}}{4*\pi*10^{-7}*16*10^{-4}} = 497{,}611 \text{ A.t/WB}$$

$$\Re_{total} = \Re + \Re_g = 501590 \text{ A.t/WB}$$

but $\Im = \Re_{total} * \phi$

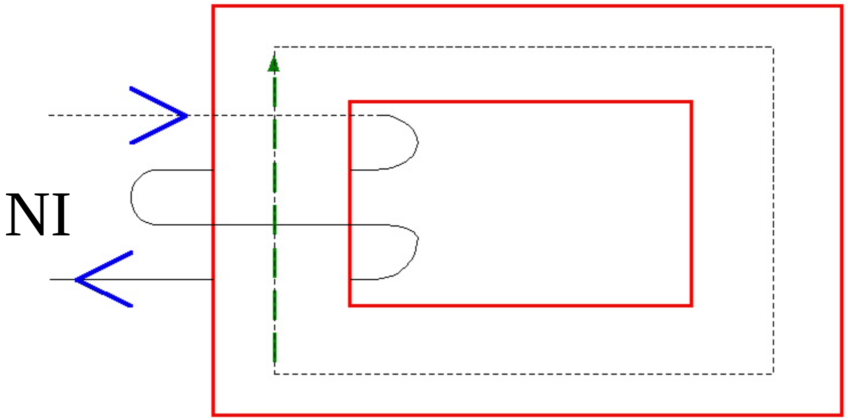
so, $NI = \Re_{total} * \phi \Rightarrow I = \dfrac{\Re * \phi}{N} = 3.44 \text{ A}$

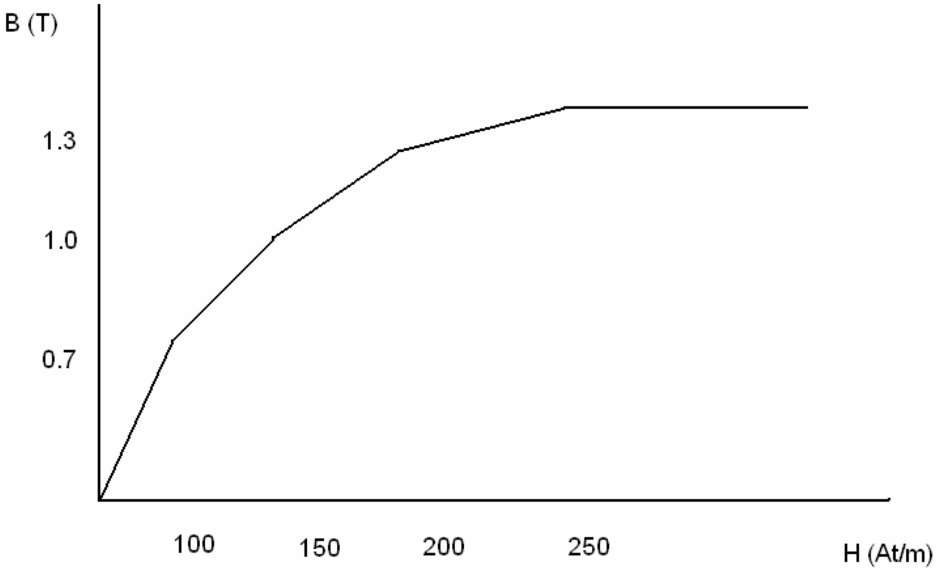
Examples

- **Example 3:** A square magnetic core has a mean path of 55 cm and a cross sectional area of 150 cm^2. A 200 turn coil of wire is wrapped around one leg as shown in the figure below. The core is made of a magnetic material having a magnetization curve as below.

(a) How much current is needed to produce 0.012 wb of flux in the core.

(b) What is the core relative permeability.





Examples

(a)

$$B = \frac{\phi}{A} = \frac{0.012}{0.015} = 0.8\,\mathrm{T}$$

$$\textit{From}\ \text{the curve} \Rightarrow \mathrm{H} \cong 110\ \text{A.t./m}$$

$$\Im = N * I = H * L \Rightarrow 200\,\mathrm{I} = 110 * 55 * 10^{-2} = 0.316A$$

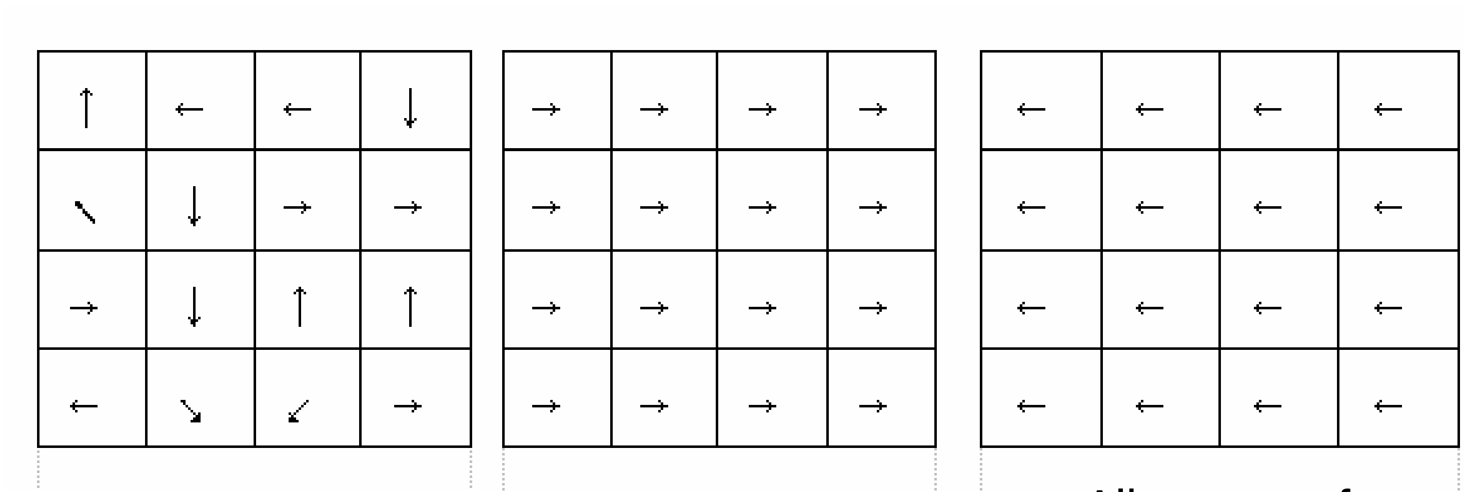
(b)

$$\mu = \frac{B}{H} = \frac{0.8}{115} = 0.00696\ \mathrm{H/m}$$

$$\text{but } \mu = \mu_o * \mu_r \Rightarrow \mu_r = 5540$$

Losses in Magnetic Materials

Hysteresis loss: occurs due to the energy that is spent in reversing the alignment of magnetic domains.



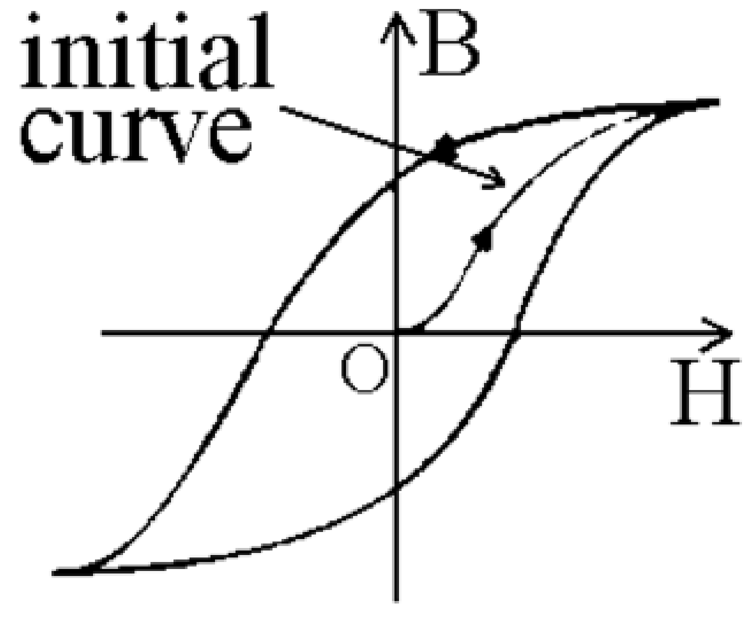
Random Distribution

Alignment of domains in one direction (AC current +)

Alignment of domains in one direction (AC current -)

Hysteresis loop for a ferromagnetic material

With AC current, as the cycle repeats, the loop traces its defined path depending on the type of magnetizing material used.



Hysteresis Loss

- Energy is spent when current changes its polarity every half cycle. Power loss due to Hysteresis is given by the equation:

$$P_h = k_h \; V \; f \; B_{max}{}^n$$

- k_h is a constant relating to the loop area
- n = 1.5 to 2.5 depending on the material
- B_{max} = Maximum flux density
- V = volume of the material.

Eddy Current Loss

- Again, is a loss in the magnetic core, that is in the iron structure, caused by the induced voltages in the iron core.

- Iron cores are laminated to reduce this loss. Laminated cores offer a much higher resistance for the flow of eddy currents in the core.

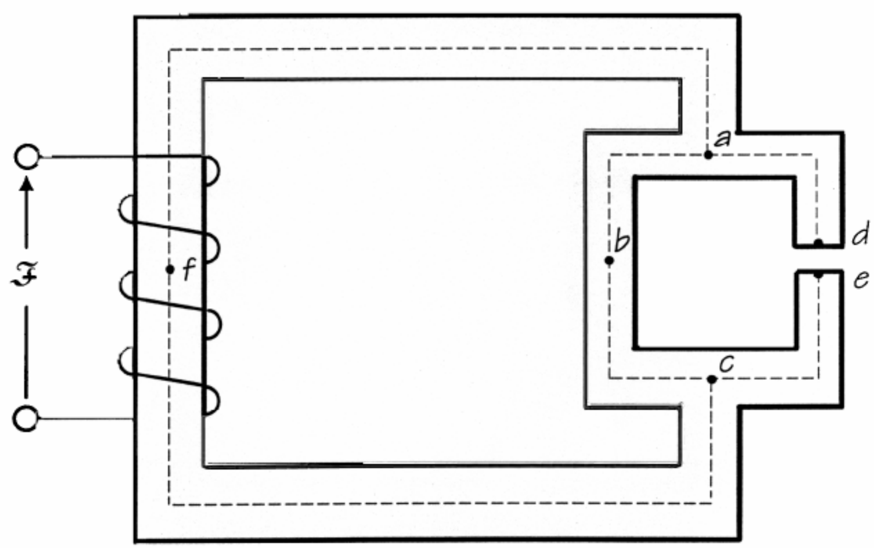
$$P_e = k_e \, (B_{max} \;\; \mathrm{t} \;\; f\,)^2$$

  - k_e - constant that depends on the material
  - t - thickness of laminations.

Home work Q. 1

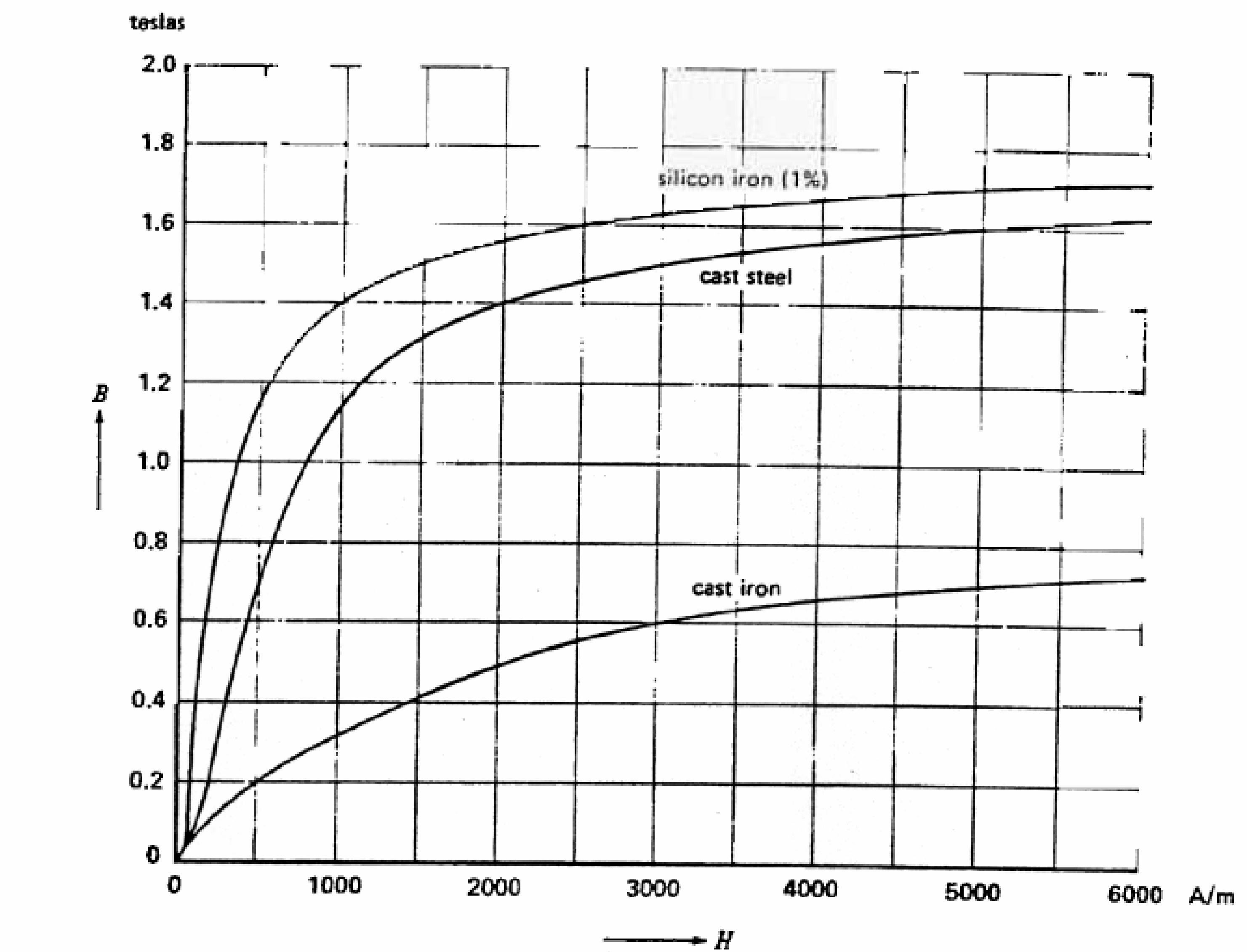
The table below is for the magnetic circuit shown below. The core is made of cast steel and its magnetization curve is provided on the next page. Determine (a) the required coil mmf to provide the specified flux; and, (b) the length of the air gap.

Path	Cross-sectional area (m^2)	Length (m)	Flux (Webers)
cfa	0.05	0.8	
abc	0.03	0.4	4.2×10^{-2}
ad	0.272	0.15	
de	0.272	?	2.8×10^{-2}
ec	0.272	0.15	



Home work

Q. 1


teslas
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
B
silicon iron (1%)
cast steel
cast iron
0
1000
2000
3000
4000
5000
6000
A/m
H

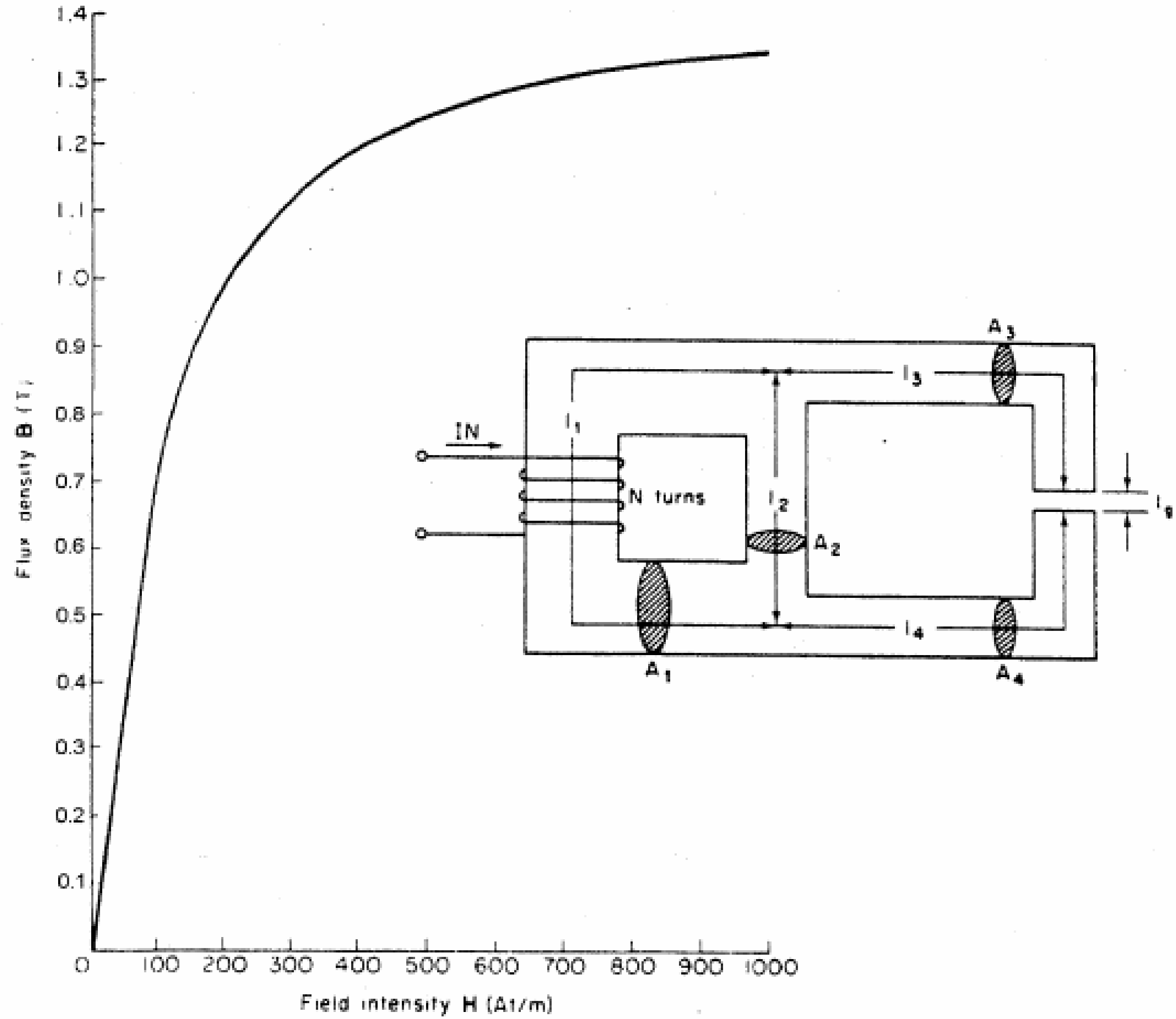
Home work

Q. 2

Find the current, I_N, required to establish a flux of 2 mWb in the air gap of the magnetic structure shown in the figure below. The structure is made of silicon sheet steel, and its magnetization curve is as shown. Assume that the coil has 500 turns, and the structure has the following dimensions:

$l_1 = 40$ cm	$A_1 = 40$ cm^2	$l_3 = l_4 = 26$ cm	$A_3 = A_4 = 25$ cm^2
$l_2 = 24$ cm	$A_2 = 12$ cm^2	$l_g = 25 \times 10^{-3}$ cm	$A_g = 26$ cm^2

Home work
Q. 2



Flux density B (T)
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100
200
300
400
500
600
700
800
900
1000
Field intensity H (At/m)
IN
N turns
l_1
l_2
l_3
l_4
l_g
A_1
A_2
A_3
A_4