Magnetic Materials

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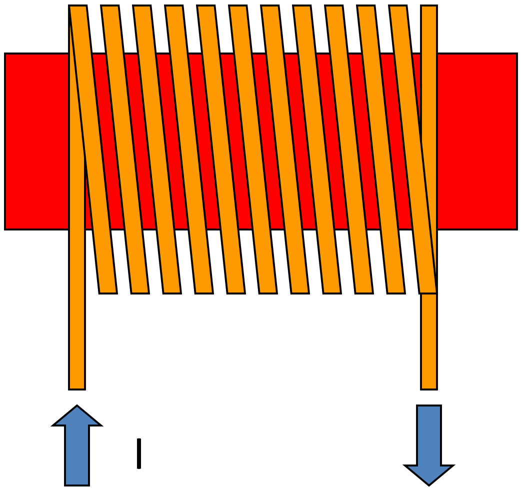
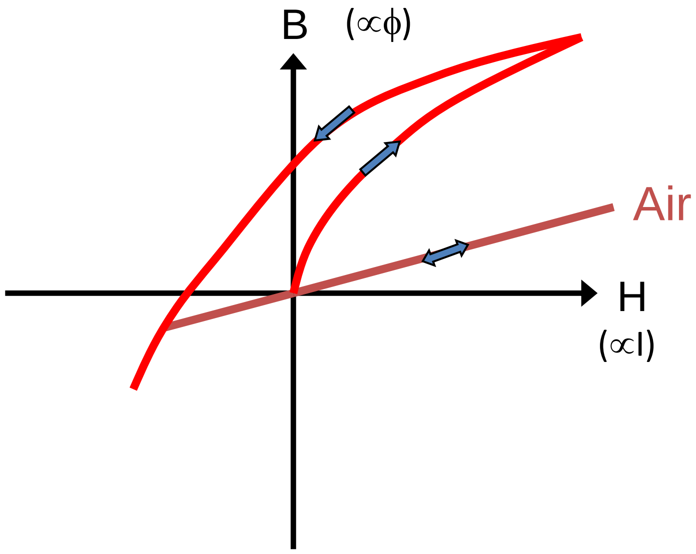
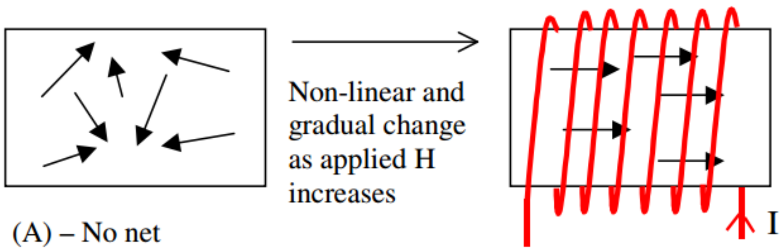




Some applications (e.g transformers and machine stators) require materials that are easy to magnetise and de-magnetise - **soft magnetic materials**

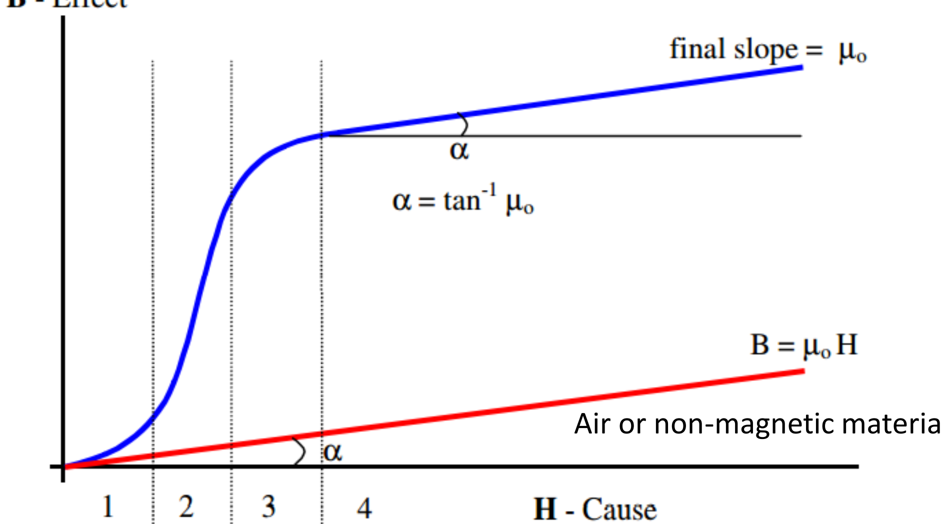
Others require materials that are difficult to de-magnetise and remain essentially permanently magnetised - hard or **permanent magnets**

Magnetisation of soft magnetic materials



(A) – No net external effect

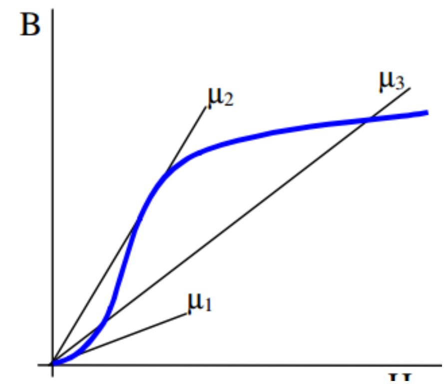
(B) – Domains aligned with applied field

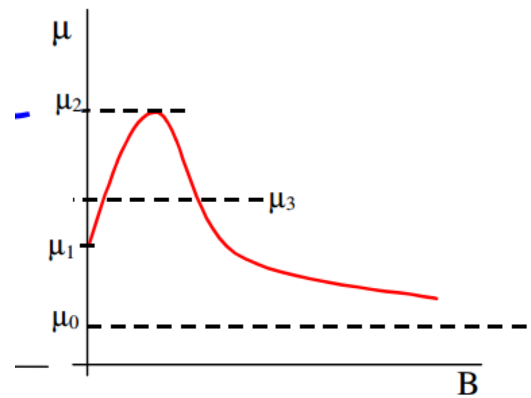


Magnetisation curve or B/H curve

1. Initial growth of closely aligned domains
2. Rapid reversal of domains
3. final rotation of domains
4. No further contribution from domains - saturation

Permeability





Almost always referred to in terms of relative permeability

$$\mu = \mu_r \mu_0$$

Soft magnetic materials for stator cores

Desirable Static properties

- High saturation flux density
  - increased flux carrying capability
- High permeability
  - reduced mmf (Ampere turns) to achieve a given flux

Desirable dynamic properties

- Low coercivity
  - reduced hysteresis loss
- High electrical resistance
  - reduced eddy current losses under AC excitation

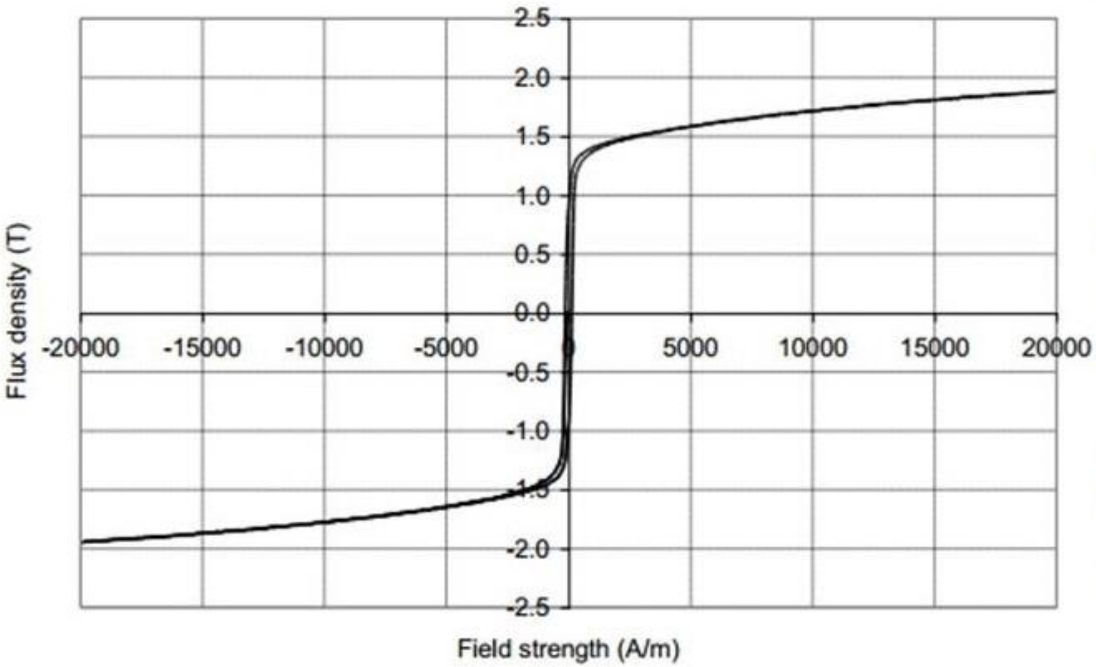
Other properties

- High thermal conductivity
  - Assists removal of losses from core and windings
- High mechanical strength
  - withstand manufacturing process
  - withstand centrifugal load in rotating parts

Focus on magneto-static properties

(we will return to dynamic properties and losses later in the course)

Typical BH characteristic for 3.5% Silicon Iron



Very high permeability up to flux densities of 1.5T (several 1000)

Gradually diminishing permeability beyond 1.5T – onset of significant magnetic saturation

Eventually saturates such that slope = μ_0 (permeability of free space) – 'physics' defintion

Magnetic saturation is a gradual process from an engineering perspective, e.g. in the example above, the permeability is dropping significantly from 1.3T onwards
'Physics' definition is based on a very precise value at which the incremental permeability reduces to μ_0 – higher than practical values used
Often design near the 'onset of significant saturation' – e.g. ~1.5T in the example above

Silicon Iron

Mainstay of electrical steels for power applications

Silicon is added to increase electrical resistivity

- reduces losses due to eddy current

Conventional SiFe electrical steels have 3-3.5% Silicon content

-compromise between electrical and mechanical properties

-can go up to 6.5% (high cost specialist material)

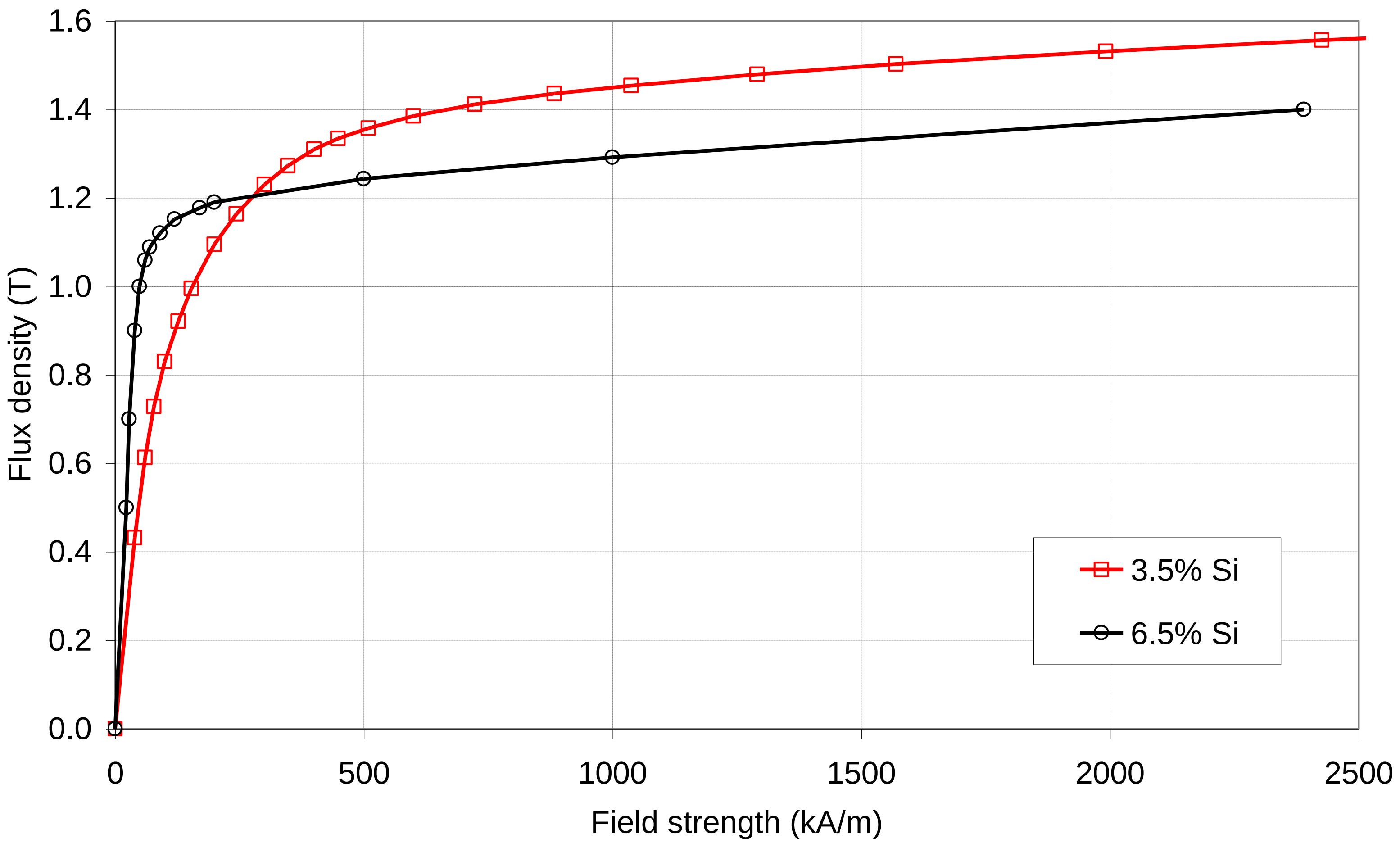
Increasing Silicon content results in a more brittle material

- important in terms of punching laminations

Increasing Silicon content suppresses saturation flux density

Vast array of different grades whose properties are optimised for different machine and transformer applications (currently dominated by 50Hz and 60Hz applications)

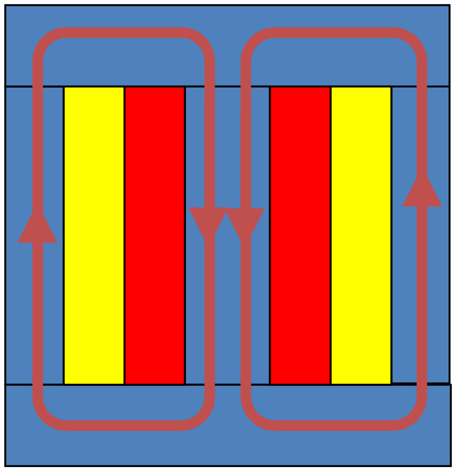
Effect of Silicon content saturation flux density

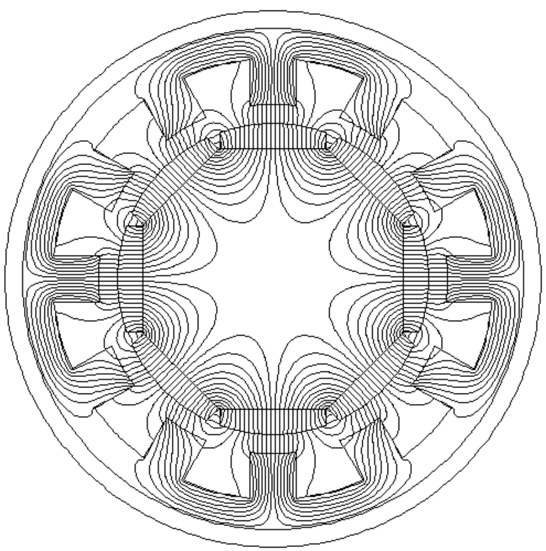


BH-curves 3.5%Si & NKK 6.5% Si

Grain oriented materials

Some devices have essentially uni-axial variations in flux, e.g transformers – only require high permeability in one direction





- Grain oriented steels are 3% silicon-iron alloys developed with very low power loss and high permeability in the rolling direction
- Extensively used in high power, high efficiency transformers
- Poor properties in orthogonal direction
- Not suitable for electrical machines – all electrical machines use **non-oriented materials**

Even within one type of material there are many different grades, e.g. 3% Silicon Iron

Variations in thickness, and heat treatment

Very little difference in static properties – many differences are in core loss properties (more about this later in the course)

Example datasheet shown is for non-oriented fully processed (upper end of price range) electrical steel (term often used for Silicon Iron in Europe)

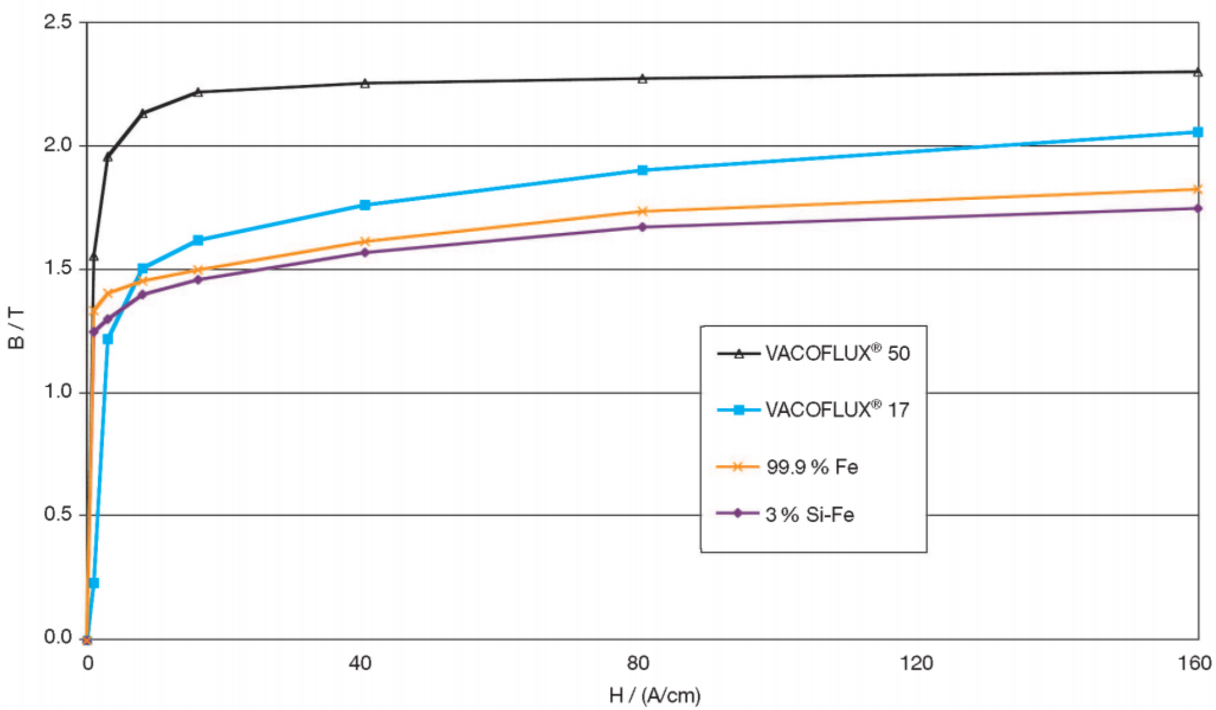
http://www.sura.se/Sura/hp_products.nsf/vOpendocument/03A8B2433FAE16C4C1256AA8002280E6/$FILE/NO-11.pdf?OpenElement

Guaranteed magnetic properties

Cogent non-oriented fully processed electrical steels are graded according to European Standard EN 10106. A comparison with other international standards is included on page 11.

SURA® Grade	Thickness	Max specific total loss at 50 Hz		Minimum magnetic polarization at 50 Hz			Conventional density
		$\hat{J}$=1,5 T	1,0T*	$\hat{H}$=2500	5000	10000 A/m	
	mm	W/kg	W/kg	T	T	T	kg/dm³
M210-27A	0,27	2,10	0,85	1,49	1,60	1,70	7,60
M235-35A	0,35	2,35	0,95	1,49	1,60	1,70	7,60
M250-35A	0,35	2,50	1,00	1,49	1,60	1,70	7,60
M270-35A	0,35	2,70	1,10	1,49	1,60	1,70	7,65
M300-35A	0,35	3,00	1,20	1,49	1,60	1,70	7,65
M330-35A	0,35	3,30	1,30	1,49	1,60	1,70	7,65
M250-50A	0,50	2,50	1,05	1,49	1,60	1,70	7,60
M270-50A	0,50	2,70	1,10	1,49	1,60	1,70	7,60
M290-50A	0,50	2,90	1,15	1,49	1,60	1,70	7,60
M310-50A	0,50	3,10	1,25	1,49	1,60	1,70	7,65
M330-50A	0,50	3,30	1,35	1,49	1,60	1,70	7,65
M350-50A	0,50	3,50	1,50	1,50	1,60	1,70	7,65
M400-50A	0,50	4,00	1,70	1,53	1,63	1,73	7,70
M470-50A	0,50	4,70	2,00	1,54	1,64	1,74	7,70
M530-50A	0,50	5,30	2,30	1,56	1,65	1,75	7,70
M530-50HP	0,50	5,30	2,30	1,63	1,71	1,81	7,80
M600-50A	0,50	6,00	2,60	1,57	1,66	1,76	7,75
M700-50A	0,50	7,00	3,00	1,60	1,69	1,77	7,80
M800-50A	0,50	8,00	3,60	1,60	1,70	1,78	7,80
M310-65A	0,65	3,10	1,25	1,49	1,60	1,70	7,60
M330-65A	0,65	3,30	1,35	1,49	1,60	1,70	7,60
M350-65A	0,65	3,50	1,50	1,49	1,60	1,70	7,60
M400-65A	0,65	4,00	1,70	1,52	1,62	1,72	7,65
M470-65A	0,65	4,70	2,00	1,53	1,63	1,73	7,65
M530-65A	0,65	5,30	2,30	1,54	1,64	1,74	7,70
M600-65A	0,65	6,00	2,60	1,56	1,66	1,76	7,75
M600-65HP	0,65	6,00	2,60	1,63	1,72	1,82	7,80
M700-65A	0,65	7,00	3,00	1,57	1,67	1,76	7,75
M800-65A	0,65	8,00	3,60	1,60	1,70	1,78	7,80
M600-100A	1,00	6,00	2,60	1,53	1,63	1,72	7,60
M700-100A	1,00	7,00	3,00	1,54	1,64	1,73	7,65
M800-100A	1,00	8,00	3,60	1,56	1,66	1,75	7,70
M1000-100A	1,00	10,00	4,40	1,58	1,68	1,76	7,80

Range of properties of high performance soft magnetic materials



VACOLFUX 50: High cobalt content (49%) Cobalt-Iron alloy

http://www.vacuumschmelze.com/fileadmin/Medienbiliothek_2010/Downloads/HT/PHT_004_Vacoflux-Vacodur_engl.pdf

Silicon Iron (which contains ~3% Silicon) is a relatively low cost material (approx £1-£2 per kg depending on grade and lamination thickness)

• Provides a reasonable compromise between high electrical resistivity (useful for reducing eddy current losses) and saturation flux density (~2.03T according to 'physics' definition)
• Cobalt Iron, specifically the grades with ~49% Cobalt content (saturation flux density of ~2.35T)
• Very expensive (order of £100 per kg depending on quantity and grade)
• Use in electrical machines is usually limited to aerospace and motor-sport where the very substantial cost premium can be tolerated (80-100 times the cost for ~15% higher performance!)

Range of available properties

Nickel irons

SiFe

Pure Iron

CoFe

Material	Permeability μ_4	Permeability μ_{max}	Coercivity (A/cm)	Saturation polarization (T)
MUMETALL	60000	250000	0.015	0.80
VACOPERM 100	200000	350000	0.01	0.74
PERMENORM 5000 H2	7000	120000	0.05	1.55
PERMENORM 5000 V5	9000	135000	0.04	1.55
PERMENORM 5000 S4	15000	150000	0.025	1.60
RECOVAC 50	3500	30000	0.15	1.35
MEGAPERM 40L	6000	80000	0.06	1.48
CHRONOPERM 36	6000	50000	0.05	0.75
PERMENORM 3601 K5	4000	50000	0.1	1.30
TRAFOPERM N3	1000	30000	0.2	2.03
VACOFER S1	2000	40000	0.06	2.15
VACOFLUX 50	1000	9000	1.4	2.35
VACOFLUX 17	600	4000	1.5	2.22

Selection of a material for a given application is complex function of performance and COST