Magnetism and Magnetic Recording Media

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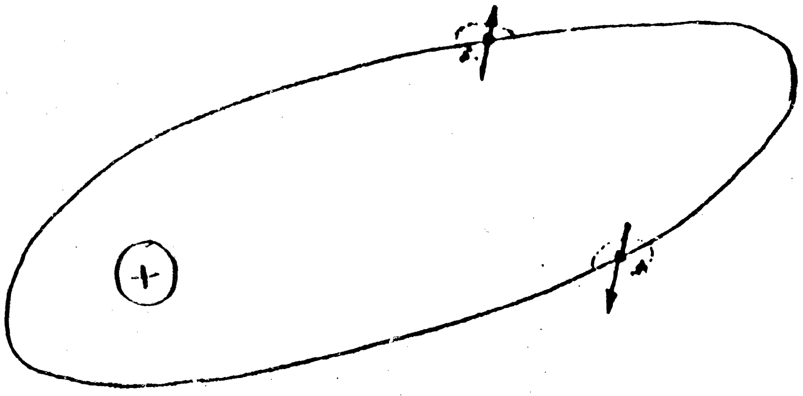
Contents

IN MAGNETISM **ELECTRONS** ARE ALL-IMPORTANT

ORBITAL MOTION AND SPIN

- THE NUCLEUS WILL NOT BE CONSIDERED FURTHER
- ELECTRONS ARE TRAVELLING IN WELL-DEFINED ORBITS
- ELECTRONS SHARING THE SAME ORBIT WILL HAVE OPPOSITE SPIN



- THERE ARE MAGNETIC MOMENTS ASSOCIATED WITH BOTH THE ORBITAL MOTION AND THE SPIN OF THE ELECTRON
- THE **ELECTRON SPIN** IS THE REAL KEY TO **MAGNETISM**

Fundamental unit of magnetism

$\mu_B = \frac{eh}{4\pi mc}$

magnetic moment /atom, $\mu = n\mu_B$

μ_B (Bohr Magneton) $= 9.27 \times 10^{-24}$ Am^2

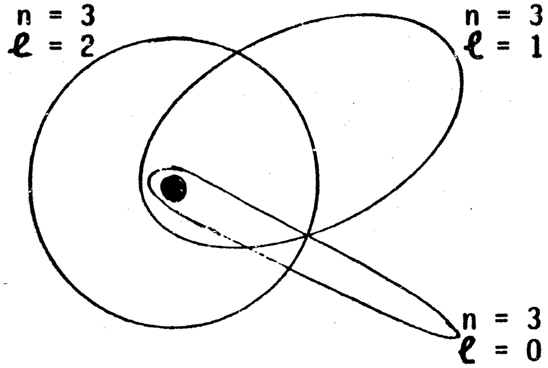
$= 0.927 \times 10^{-20}$ erg/

THE FOUR QUANTUM NUMBERS (PAULI)

1) PRINCIPAL QUANTUM NUMBER, n

$$mvr = \frac{nh}{2\pi}$$

2) AZIMUTHAL QUANTUM NUMBER, ℓ

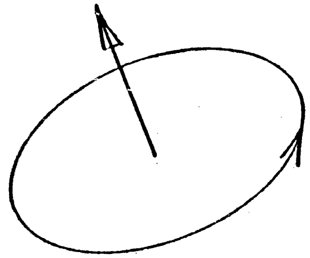


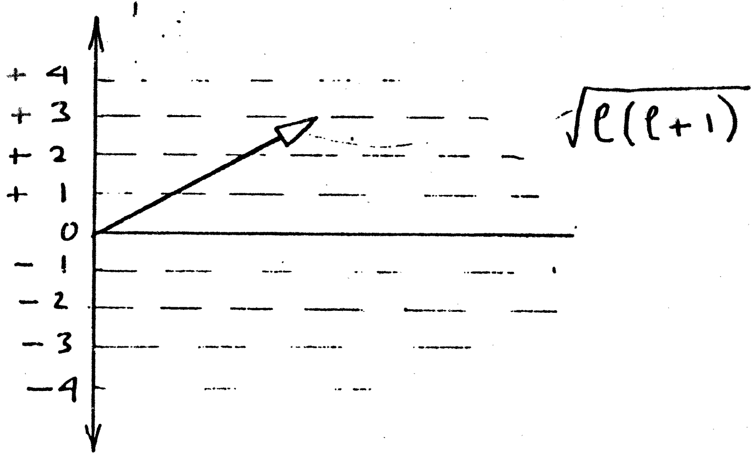
POSSIBLE VALUES

$$\ell \leq n - 1$$

MOST ELLIPTICAL ORBITS = MOST TIGHTLY BOUND ELECTRON
= LOWEST ENERGY

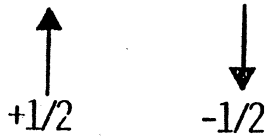
3) MAGNETIC QUANTUM NUMBER, m_ℓ



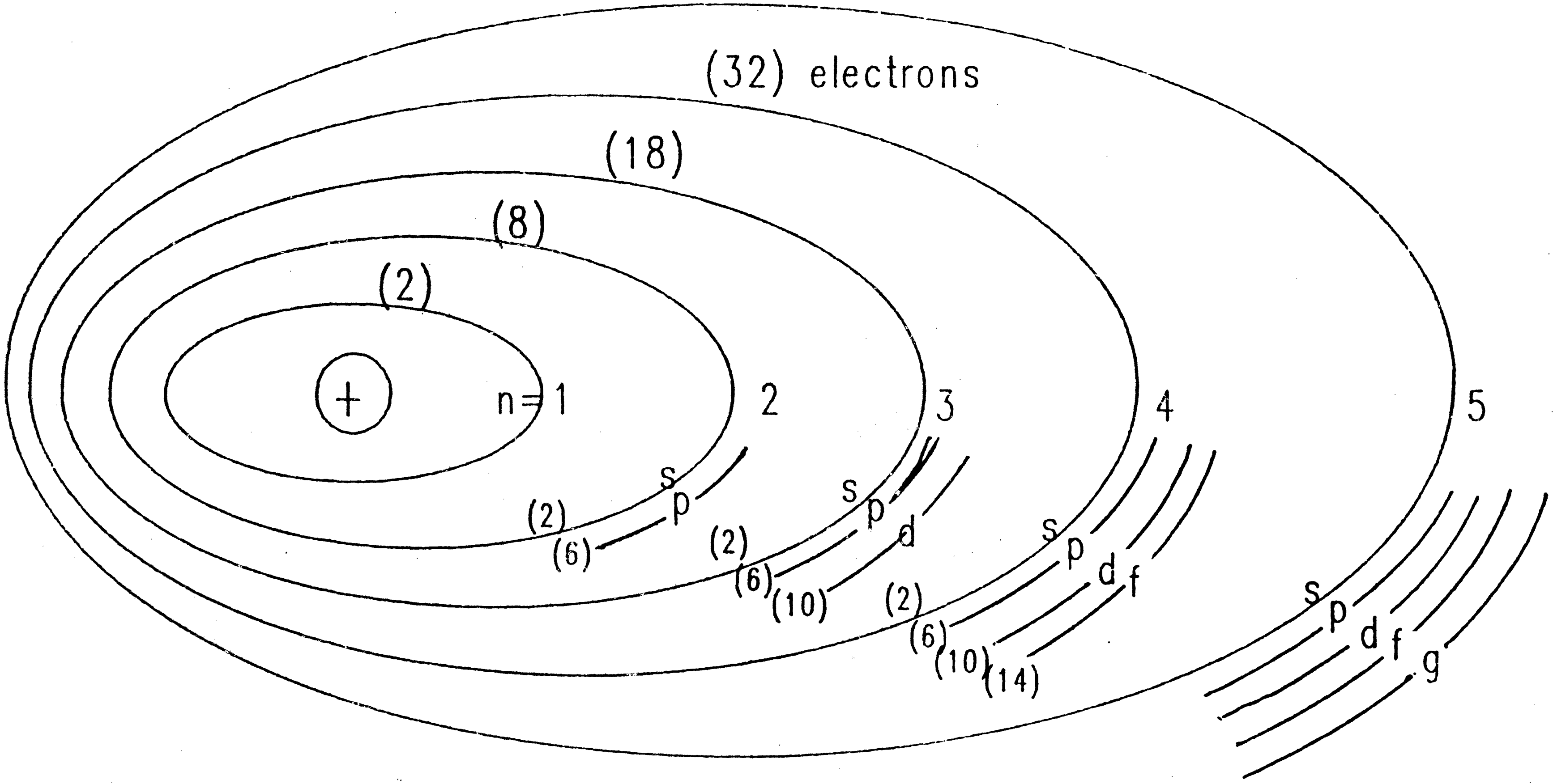


possible values $+\ell, +(\ell-1), +(\ell-2) - - - - +1, 0, -1, - - - - -\ell$

4) SPIN QUANTUM NUMBER



Atomic Orbitals



PERIODIC TABLE, MASS SUSCEPTIBILITIES

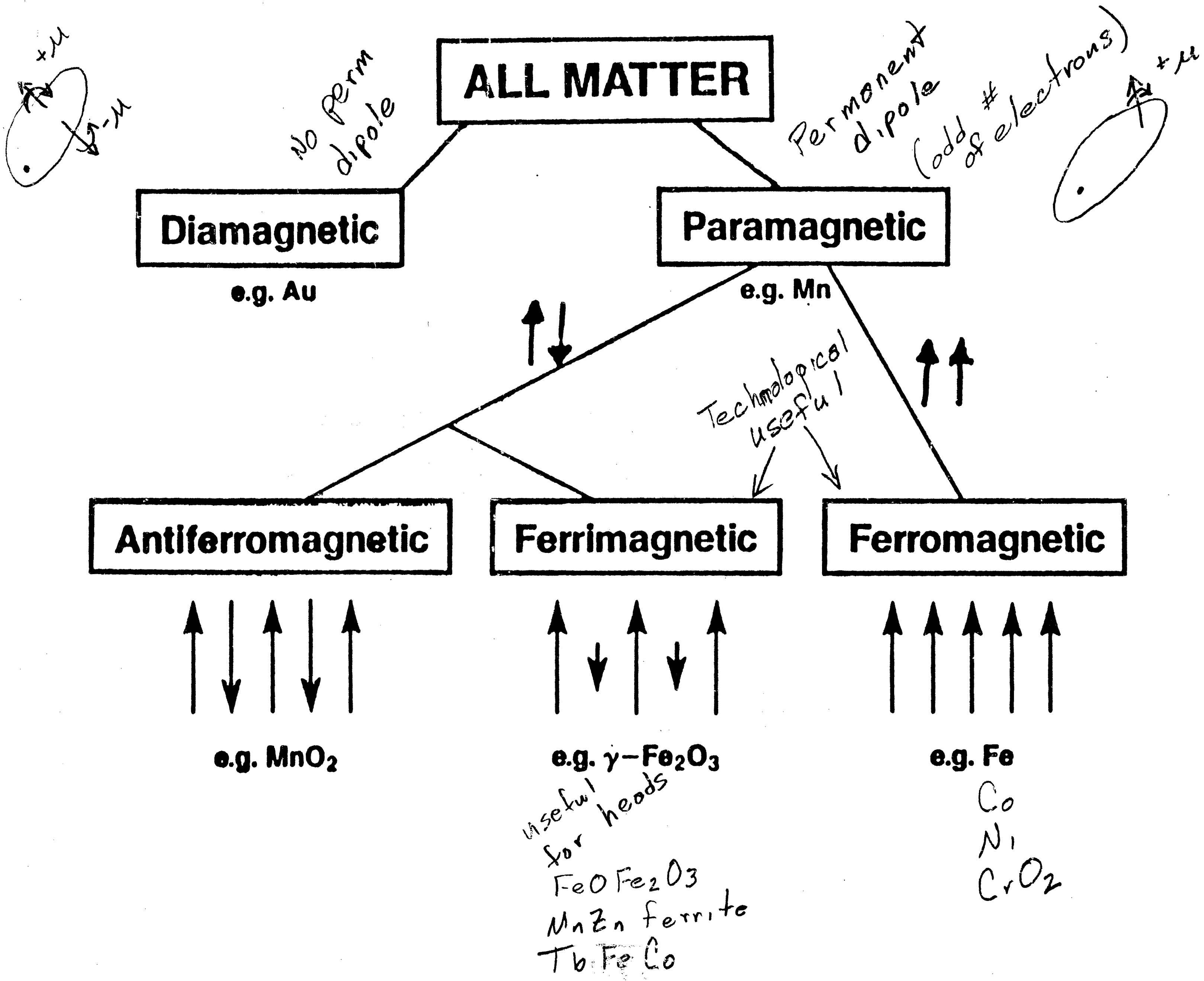
elements of 1st transition ↓

	K 1s	L 2s 2p	M 3s 3p 3d	N 4s 4p 4d 4f	O 5s 5p 5d	P 6s 6p 6d	Q 7s	Ground term	χ × 10⁶
H 1	1							$^{2}S_{\frac{1}{2}}$	−1·97
He 2	2							$^{1}S_{0}$	−0·47
Li 3	2	1						$^{2}S_{\frac{1}{2}}$	+0·50
Be 4	2	2						$^{1}S_{0}$	−1·00
B 5	2	2 1						$^{2}P_{\frac{1}{2}}$	−0·62
C 6	2	2 2						$^{3}P_{0}$	−0·49
N 7	2	2 3						$^{4}S_{1\frac{1}{2}}$	−0·8
O 8	2	2 4						$^{3}P_{2}$	+106·2
F 9	2	2 5						$^{2}P_{1\frac{1}{2}}$	—
Ne 10	2	2 6						$^{1}S_{0}$	−0·33
Na 11	10 Ne core		1					$^{2}S_{\frac{1}{2}}$	+0·51
Mg 12			2					$^{1}S_{0}$	+0·55
Al 13			2 1					$^{2}P_{\frac{1}{2}}$	+0·65
Si 14			2 2					$^{3}P_{0}$	−0·13
P 15			2 3					$^{4}S_{1\frac{1}{2}}$	−0·90
S 16			2 4					$^{3}P_{2}$	−0·49
Cl 17			2 5					$^{2}P_{1\frac{1}{2}}$	−0·57?
A 18	2	2 6	2 6					$^{1}S_{0}$	−0·48
K 19	18 A core			1				$^{2}S_{\frac{1}{2}}$	+0·52
Ca 20				2				$^{1}S_{0}$	+1·10
Sc 21			1	2				$^{2}D_{1\frac{1}{2}}$	—
Ti 22			2	2				$^{3}F_{2}$	+1·25
V 23			3	2				$^{4}F_{1\frac{1}{2}}$	+1·4
Cr 24			5	1				$^{7}S_{3}$	+3·08
Mn 25			5	2				$^{6}S_{2\frac{1}{2}}$	+11·8
Fe 26			6	2				$^{5}D_{4}$	Ferro.
Co 27			7	2				$^{4}F_{4\frac{1}{2}}$	,,
Ni 28			8	2				$^{3}F_{4}$	,,
Cu⁺	2	2 6	2 6 10					$^{1}S_{0}$	
Cu 29	28 Cu⁺ core			1				$^{2}S_{\frac{1}{2}}$	−0·086
Zn 30				2				$^{1}S_{0}$	−0·157
Ga 31				2 1				$^{2}P_{\frac{1}{2}}$	−0·24
Ge 32				2 2				$^{3}P_{0}$	−0·12
As 33				2 3				$^{4}S_{1\frac{1}{2}}$	−0·31
Se 34				2 4				$^{3}P_{2}$	−0·32
Br 35				2 5				$^{2}P_{1\frac{1}{2}}$	−0·39
Kr 36	2	2 6	2 6 10	2 6				$^{1}S_{0}$	−0·35
Rb 37	36 Kr core				1			$^{2}S_{\frac{1}{2}}$	+0·21
Sr 38					2			$^{1}S_{0}$	−0·20
Y 39				1	2			$^{2}D_{1\frac{1}{2}}$	+5·3
Zr 40				2	2			$^{3}F_{2}$	−0·45
Cb 41				4	1			$^{6}D_{\frac{1}{2}}$	+1·5
Mo 42				5	1			$^{7}S_{3}$	+0·04
Ma 43				5	2			—	—
Ru 44				7	1			$^{5}F_{5}$	+0·50
Rh 45				8	1			$^{4}F_{4\frac{1}{2}}$	+1·11
Pd 46	2	2 6	2 6 10	2 6 10				$^{1}S_{0}$	+5·4

magnetic properties

Rare earth

	K 1s	L 2s 2p	M 3s 3p 3d	N 4s 4p 4d 4f	O 5s 5p 5d	P 6s 6p 6d	Q 7s	Ground term	χ × 10⁶
Ag 47	46 Pd core				1			$^{2}S_{\frac{1}{2}}$	−0·20
Cd 48					2			$^{1}S_{0}$	−0·18
In 49					2 1			$^{2}P_{\frac{1}{2}}$	−0·11
Sn 50					2 2			$^{3}P_{0}$	−0·25
Sb 51					2 3			$^{4}S_{1\frac{1}{2}}$	−0·87
Te 52					2 4			$^{3}P_{2}$	−0·31
I 53					2 5			$^{2}P_{1\frac{1}{2}}$	−0·36
Xe 54	2	2 6	2 6 10	2 6 10	2 6			$^{1}S_{0}$	−0·34
Cs 55	54 Xe core					1		$^{2}S_{\frac{1}{2}}$	−0·22
Ba 56						2		$^{1}S_{0}$	+0·9
La 57					Xe core 1	2		$^{2}D_{1\frac{1}{2}}$	+1·04
Ce 58				1	1	2		$^{3}H_{4}$	+15·0
Pr 59				2	1	2		—	+25·0
Nd 60				3	1	2		—	+36·0
Il 61				4	1	2		—	—
Sm 62				6		2		$^{7}F_{0}$	—
Eu 63				7	Xe core	2		$^{8}S_{3\frac{1}{2}}$	+22·0
Gd 64				7	1	2		$^{9}D_{2}$	Ferro.
Tb 65	54 Xe core			8	1	2		—	—
Dy 66				9	1	2		—	—
Ho 67				10	1	2		—	—
Er 68				11	1	2		—	—
Tu 69				13		2		—	—
Yb 70				14		2		—	—
Lu⁺⁺⁺	2	2 6	2 6 10	2 6 10 14	2 6				
Lu 71	68 Lu⁺⁺⁺ core				1	2		$^{2}D_{1\frac{1}{2}}$	—
Hf 72					2	2		$^{3}F_{2}$	—
Ta 73					3	2		($^{4}F_{1\frac{1}{2}}$)	+0·87
W 74					4	2		$^{5}D_{0}$	+0·28
Re 75					5	2		$^{6}S_{2\frac{1}{2}}$	—
Os 76					6	2		($^{5}D_{4}$)	+0·05
Ir 77					9			$^{4}D_{3\frac{1}{2}}$?	+0·15
Pt 78					9	1		$^{3}D_{3}$	+1·10
Au⁺	2	2 6	2 6 10	2 6 10 14	2 6 10			$^{1}S_{0}$	—
Au 79	78 Au⁺ core					1		$^{2}S_{\frac{1}{2}}$	−0·15
Hg 80						2		$^{1}S_{0}$	−0·168
Tl 81						2 1		$^{2}P_{\frac{1}{2}}$	−0·24
Pb 82						2 2		$^{3}P_{0}$	−0·12
Bi 83						2 3		$^{4}S_{1\frac{1}{2}}$	−1·35
Po 84						2 4		($^{3}P_{2}$)	—
At 85						2 5		—	—
Rn 86	2	2 6	2 6 10	2 6 10 14	2 6 10	2 6		$^{1}S_{0}$	
Fr 87	86 Rn core						1	—	—
Ra 88							2	$^{1}S_{0}$	—
Ac 89						1	2	($^{2}D_{1\frac{1}{2}}$)	—
Th 90						2	2	($^{3}F_{2}$)	+0·11
Pa 91						3	2	($^{4}F_{1\frac{1}{2}}$)	+2·6
U 92						4	2	($^{5}D_{0}$)	+1·78



ALL MATTER

No perm dipole

Diamagnetic

e.g. Au

Permanent dipole (odd # of electrons)

Paramagnetic

e.g. Mn

Technological useful

Antiferromagnetic

e.g. MnO_2

Ferrimagnetic

e.g. $\gamma-Fe_2O_3$

useful for heads

$FeO\ Fe_2O_3$

MnZn ferrite

TbFeCo

Ferromagnetic

e.g. Fe

Co

Ni

CrO_2

BATE

QUANTUM THEORY OF FERROMAGNETISM

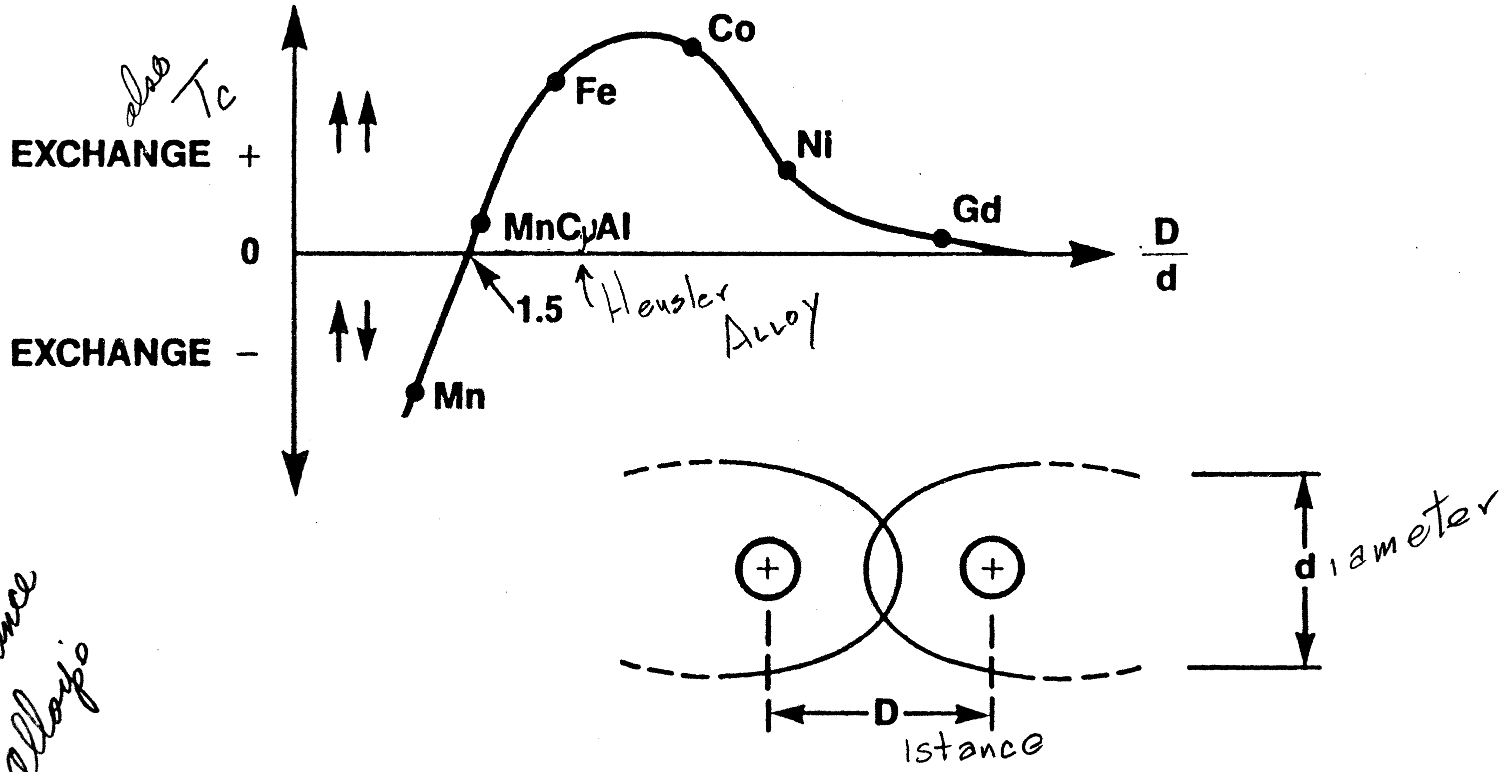
"IF ONE DEMANDS A THEORY THAT WILL PREDICT IN ADVANCE JUST WHICH ALLOYS WILL BE FERROMAGNETIC, WHAT QUANTITATIVELY WILL BE THE REMANENCE, HYSTERESIS, ETC. THEN ONE MUST ADMIT FAILURE.

. . . . IF, ON THE OTHER HAND, WHAT ONE DESIRES OF A THEORY IS A QUALITATIVE UNDERSTANDING OF WHY NATURE WORKS AS IT DOES, AND THE SATISFYING CONFIDENCE OF HAVING A MECHANISM WHICH WOULD, NO DOUBT, EXPLAIN EVEN THE MOST COMPLICATED PHENOMENA IF THE DIFFICULT MATHEMATICAL CALCULATIONS COULD BE MADE THEN THE QUANTUM THEORY OF FERROMAGNETISM IS CERTAINLY A SUCCESS."

JOHN H. VAN VLECK

C.P

EXCHANGE INTERACTION



change distance with alloys

Total Interaction = Coulomb Interaction + Exchange

	Cr	Mn	Fe	Co	Ni	Gd
D/d	1.45	1.47	1.63	1.82	1.97	3.1
T_cK			1043	1400	631	287
T_nK	475	100				

MAGNETIC PROPERTIES

Intrinsic

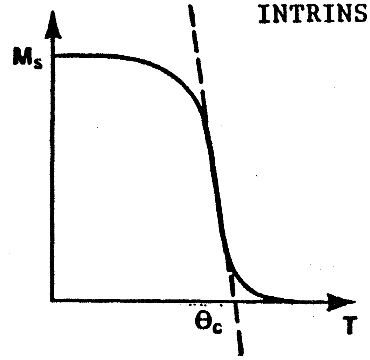
saturation magnetization, Ms

Curie temperature, Θ_c

magneto-crystalline anisotropy, K_1, K_2

magnetostriction λ

$B = H + 4\pi M_s$



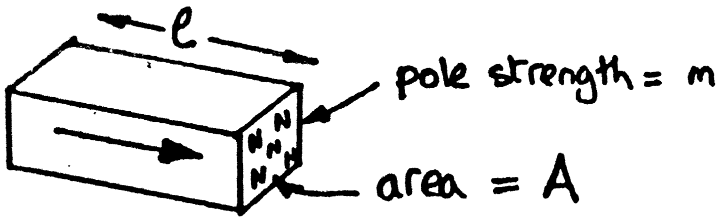
INTRINSIC PROPERTIES DEPEND ONLY ON:

- the type of atom e.g., Fe^{2+}, Fe^{3+}, Ni, Mn
- the number of atoms
- their arrangement in the crystal
- and the temperature

SATURATION MAGNETIZATION (M_S) In a magnetic field of 100 oersteds

Diamagnetic e.g. Au	-4×10^{-3} emu/cc
Paramagnetic e.g. Mn	$+10^{-1}$
Antiferromagnetic e.g. MnO_2	$+10^{-1}$
Ferrimagnetic e.g. $\gamma-Fe_2O_3$	+400
Ferromagnetic e.g. Fe	+1700

B, H, and M



magnetic moment = $m\ell$

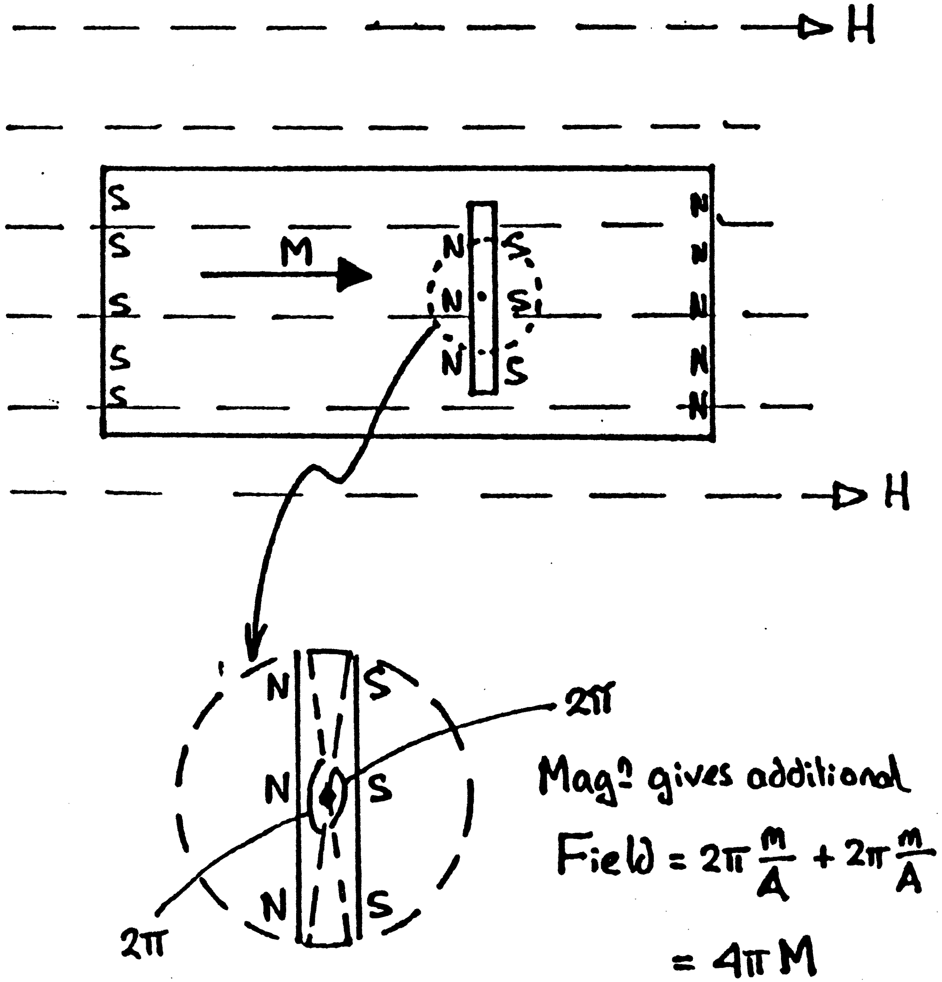
volume = $A\ell$

mag. mom./volume = $M = \frac{m}{A}$

div $\vec{B} = 0$

normal compnt $\vec{B}$ is continuous

tangential " $\vec{H}$ " "

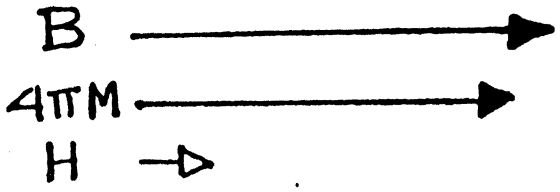


Magn gives additional

Field = $2\pi\frac{m}{A} + 2\pi\frac{m}{A}$

$= 4\pi M$

$$\underset{\text{gauss}}{B} = \underset{\text{oersteds}}{H} + 4\pi \underset{\text{emu/cc}}{M}$$



UNITS IN MAGNETISM

Quantity	Symbol	cgs units	×	factor	=	SI units
		$\boxed{B = H + 4\pi M}$				$\boxed{B = \mu_0 (H + M)}$
• magnetic flux density	B	gauss (G)	×	10^{-4}	=	Tesla (T), Webers/m²
• magnetic flux	Φ	maxwell (Mx) (G. cm²)	×	10^{-8}	=	Webers
• magnetic potential diff. (magneto-motive force)	u	gilbert (Gb)	×	$\frac{10}{4\pi}$	=	ampere (A)
• magnetic field strength	H	oersted (Oe.)	×	$\frac{10^3}{4\pi}$	=	A/m
• magnetization (per volume)	M	emu/cc	×	10^3	=	A/m
" (per mass)	σ	emu/g	×	1	=	A.m²/kg
• magnetic moment	m	emu	×	10^{-3}	=	A.m²
• susceptibility (vol.)	χ	dimensionless	×	4π	=	dimensionless
" (mass)	κ	"	×	4π	=	"
• permeability (vacuum)	μ_0	"	×	$4\pi . 10^{-7}$	=	Wb/A.m
" (material)	μ	"	×	$4\pi . 10^{-7}$	=	Wb/A.m
• Bohr magneton	μ_B	= 0.927×10^{-20} erg/oe.	×	10^{-3}	=	Am²
• demagnetizing factor	N	iensionless	×	$1/4\pi$	=	dimensionless

BATE

Elements of First Transition Series

	Fe	Co	Ni
density, g/cm^3	7.874	8.78–8.85	8.90
Curie point, °C	770	1131	358
melting point, °C	1539	1495	1455
σ 20°K, emu/g	217.75	161	54.39
σ 0°K, emu/g	221.89	162.5	57.50
M_s, emu/cm^3	1714	1422	484.1

Iron

$$\alpha \xrightarrow[910^\circ C]{} \gamma \xrightarrow[1400^\circ C]{} \alpha$$

bcc fcc

2.861 Å

Cobalt

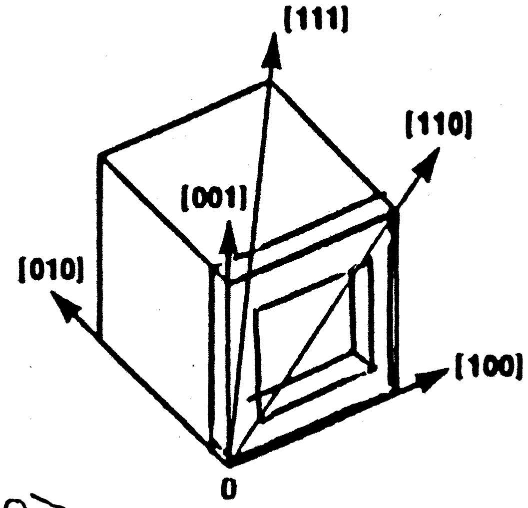
$$\text{hcp} \xrightarrow[425^\circ C]{} \text{fcc}$$

c=4.0611 3.5368
a=2.5020

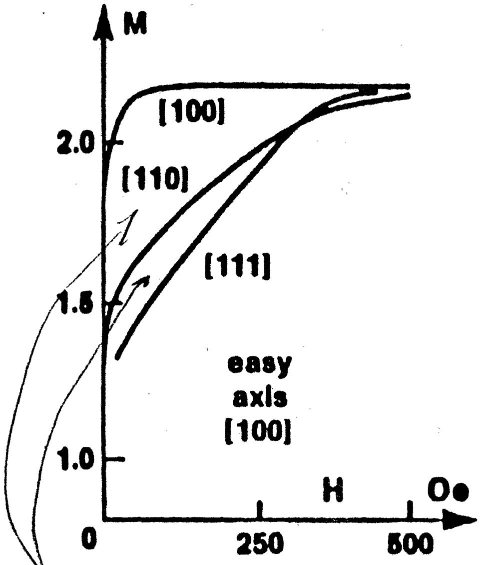
MAGNETO-CRYSTALLINE ANISOTROPY

Iron And Nickel

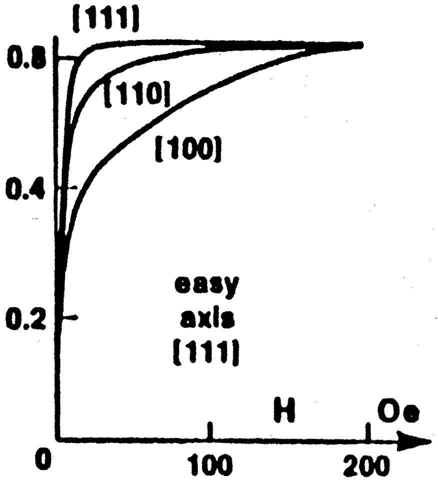
Magnetic properties related to crystal properties



IRON



NICKEL



$\langle 100 \rangle$

$= [100], [010], [001]$

$K_1 = 4.8 \times 10^5$ erg/cc

$K_2 = 5 \times 10^4$

$K_1 = -4.5 \times 10^4$

$K_2 = 2.34 \times 10^4$

magneto-crystalline energy $= K_0 + K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_2(\alpha_1^2 \cdot \alpha_2^2 \cdot \alpha_3^2) + \cdots$

Int.

MAGNETOCRYSTALLINE ANISOTROPY

relationship between K_1, K_2 and EASY directions

Cubic

K_1 K_2	+ $+\infty$ to $-9K_1/4$	+ $-9K_1/4$ to $-9K_1$	+ $-9K_1$ to $-\infty$	− $-\infty$ to $9\lvert K_1\rvert/4$	− $9\lvert K_1\rvert/4$ to $9\lvert K_1\rvert$	− $9\lvert K_1\rvert$ to $+\infty$
Easiest	[100]	[100]	[111]	[111]	[110]	[110]
Intermediate	[110]	[111]	[100]	[110]	[111]	[100]
Hardest	[111]	[110]	[110]	[100]	[100]	[111]

UNIAXIAL

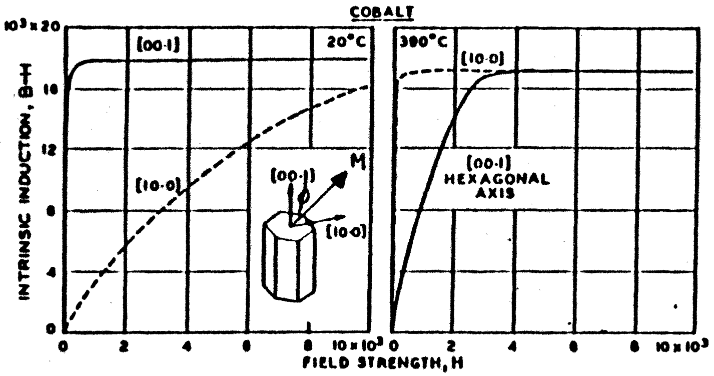
$K_1 + K_2 > 0$ axis (eg. [00.1], [100])

$K_1 + K_2 < 0$ basal plane (eg. [10.0])

R.M. Bozorth, Phys. Rev. 50, 1076-81 (1936)

G. Bate

MAGNETO - CRYSTALLINE ANISOTROPY OF COBALT



25°C 390°C

$$B = H + 4\pi M$$

$$B - H = 4\pi M$$

$$E_K = K_1 \sin^2\phi + K_2 \sin^4\phi$$

$K_1 + K_2 > 0$ [00.1] easy (hex. axis)

$K_1 + K_2 < 0$ [10.0] easy (basal plane)

Cobalt

$$K_1 = +3\cdot 98 \times 10^6 \text{ erg/cc}$$

$$K_2 = +1\cdot 98 \times 10^6 \text{ erg/cc}$$

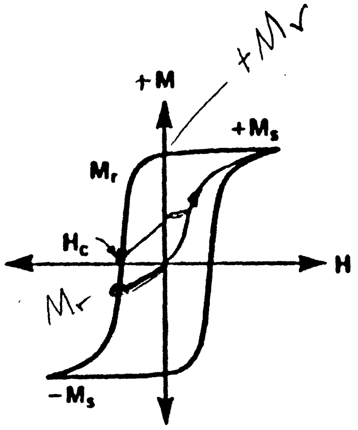
MAGNETIC PROPERTIES

Extrinsic

remanent magnetization M_r

coercivity H_c , H_r

permeability μ



EXTRINSIC PROPERTIES also depend on:

- the type, number, arrangement of the atoms
- and the temperature

but also depend on-

the <u>shape</u> and <u>size</u> of the sample

and its previous history

$$B = H + 4\pi M$$

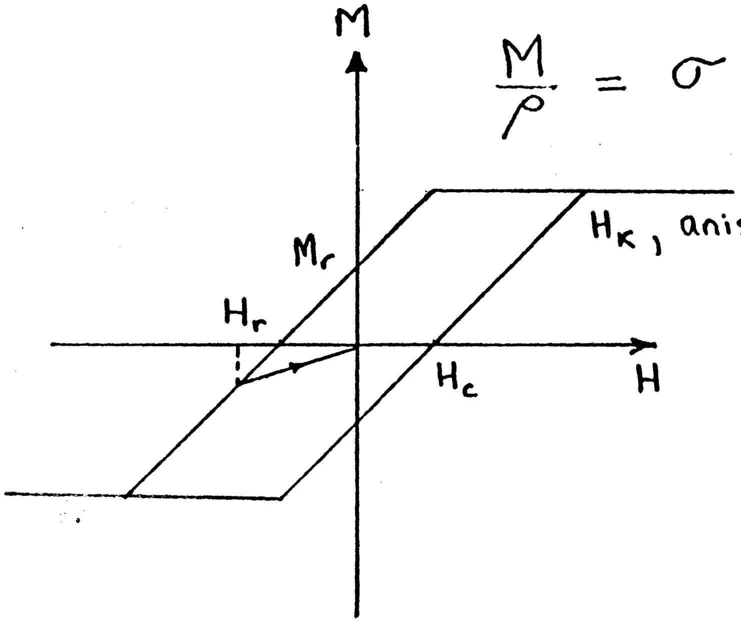
$$\mu = 1 + 4\pi \kappa$$

$$\frac{M}{\rho} = \sigma \text{ (emu/g.)}$$

$${}_{(B)}H_c < {}_{(M)}H_c$$

$$\frac{\kappa}{\rho} = \chi \text{ mass susceptibility}$$

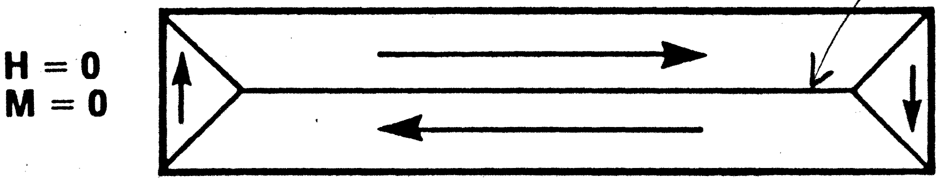
SI $B = \mu_0 (H + M)$



EXTRINSIC PROPERTIES

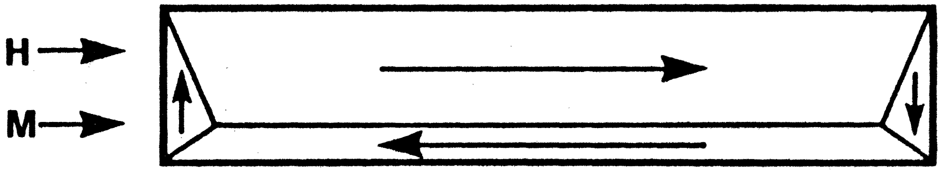
MAGNETIC DOMAINS

postulated to explain why a piece of iron

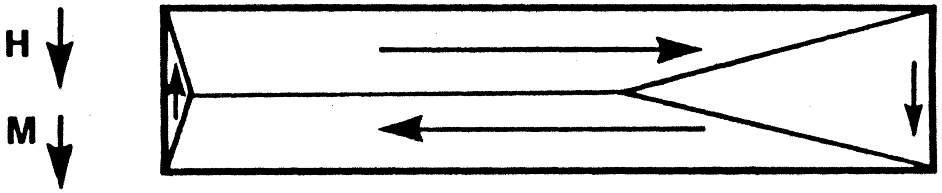


MAGNETIC DOMAIN WALL

—may not be magnetized



—may then be fully magnetized in small fields



WHAT LIMITS THE NUMBER OF DOMAINS?

DECREASE IN MAGNETOSTATIC ENERGY IS BALANCED BY THE INCREASE IN DOMAIN WALL ENERGY AND THE INCREASE IN EXCHANGE ENERGY, E_x

$E_x = JS^2\phi_0^2$ where ϕ is the angle between spins.

↑ ↓ $\phi_0 = 180^\circ$

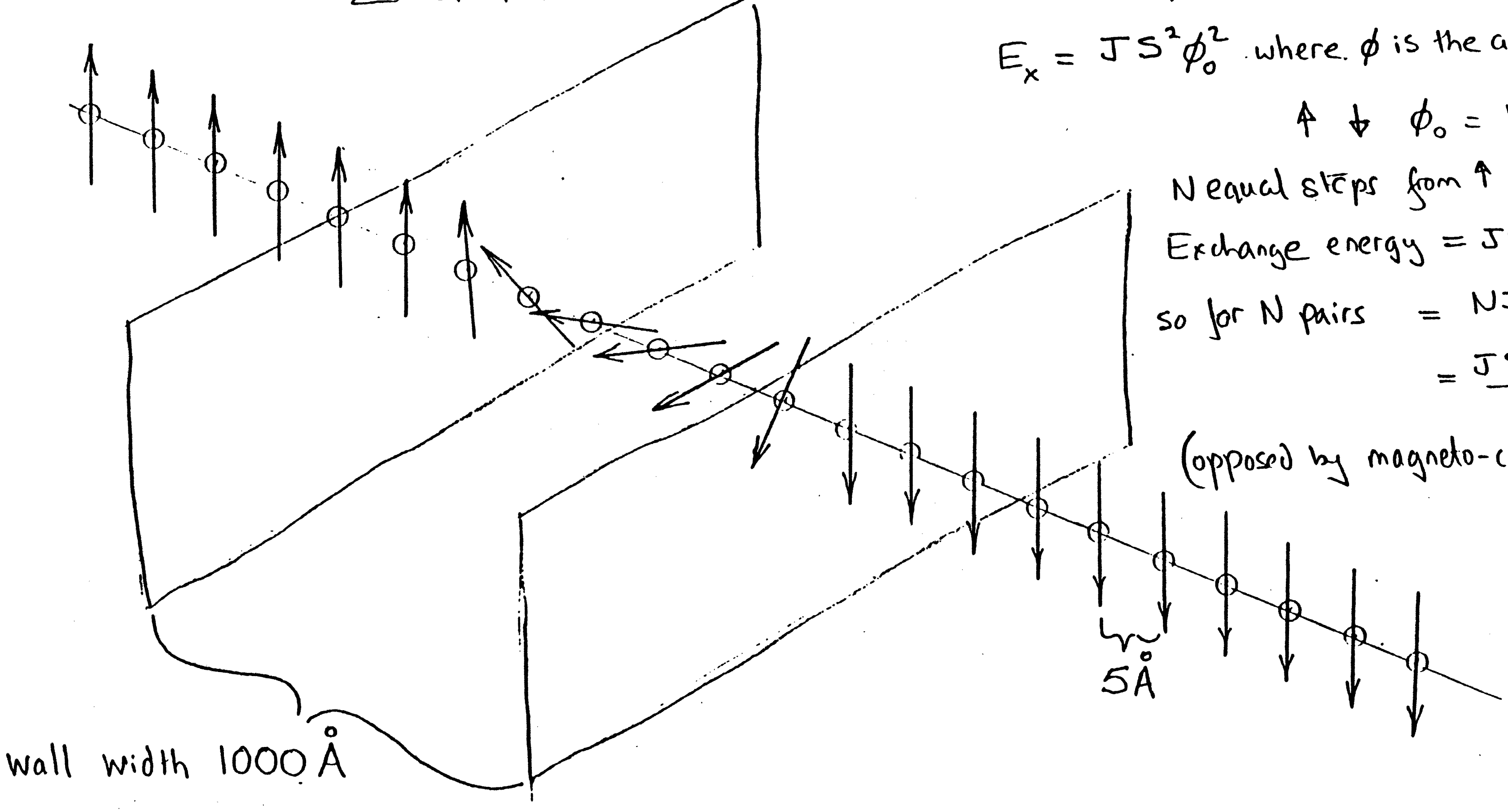
N equal steps from ↑ to ↓

Exchange energy $= JS^2\left(\frac{\phi_0}{N}\right)^2$ per p

so for N pairs $= NJS^2\left(\frac{\phi_0}{N}\right)^2$

$= \frac{JS^2\phi_0^2}{N}$

(opposed by magneto-crystalline energy)



BLOCH WALLS

$254\,\text{Å} = \frac{1}{1,000,000}''$

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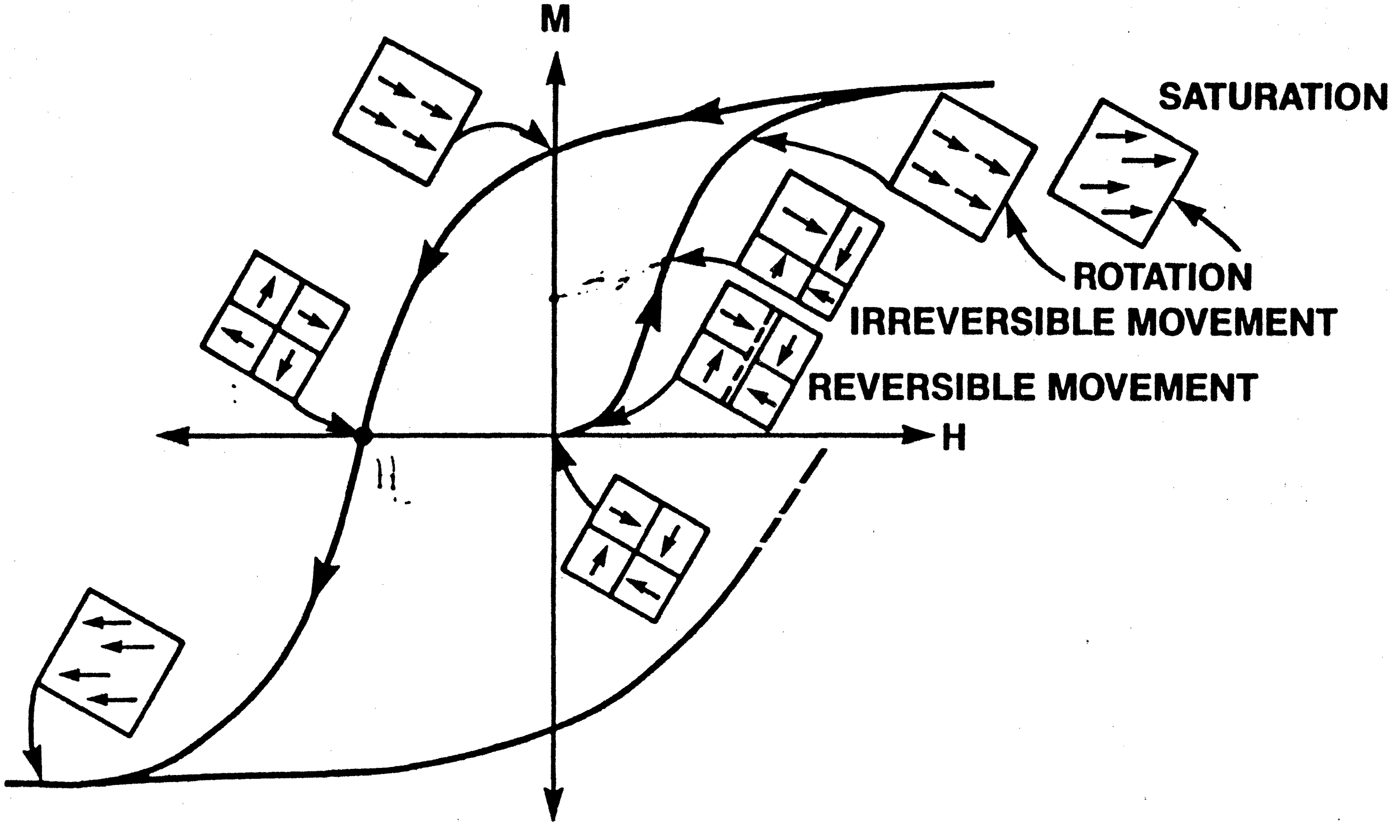
DOMAINS AND THE HYSTERESIS LOOP

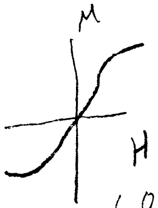


High Coercivity

Low

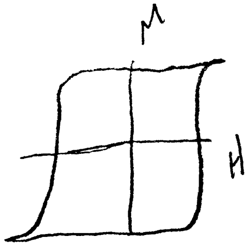
HARD AND SOFT MAGNETIC MATERIALS

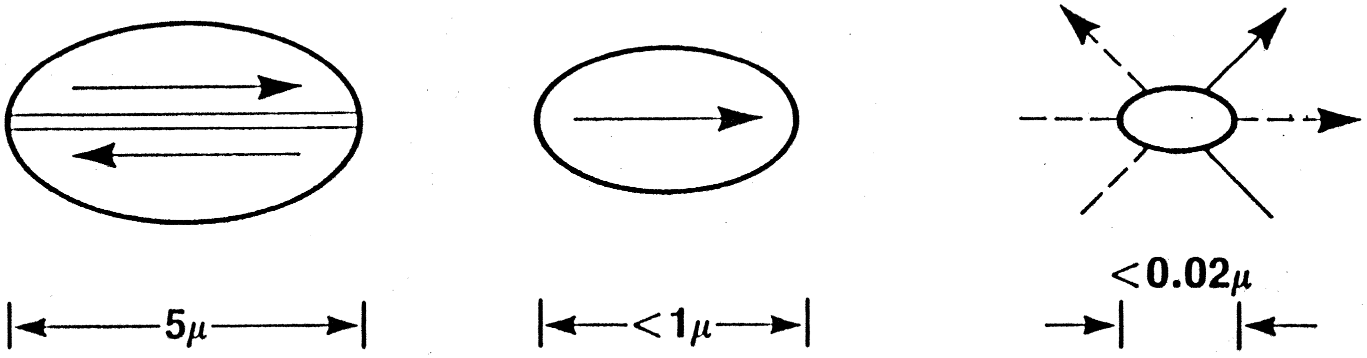
Soft	High Ms	Low Hc	Low Mr	High μ
Fe	1700 emu/cc	1 oe	<500	20,000
80Ni20Fe	660	0.1	<300	50,000
MnZn ferrite	400	0.02	<200	5,000
$Co_{70}Fe_5Si_{15}B_{10}$	530	0.1	<250	10,000

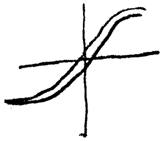
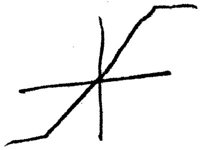


GOOD FOR HEADS

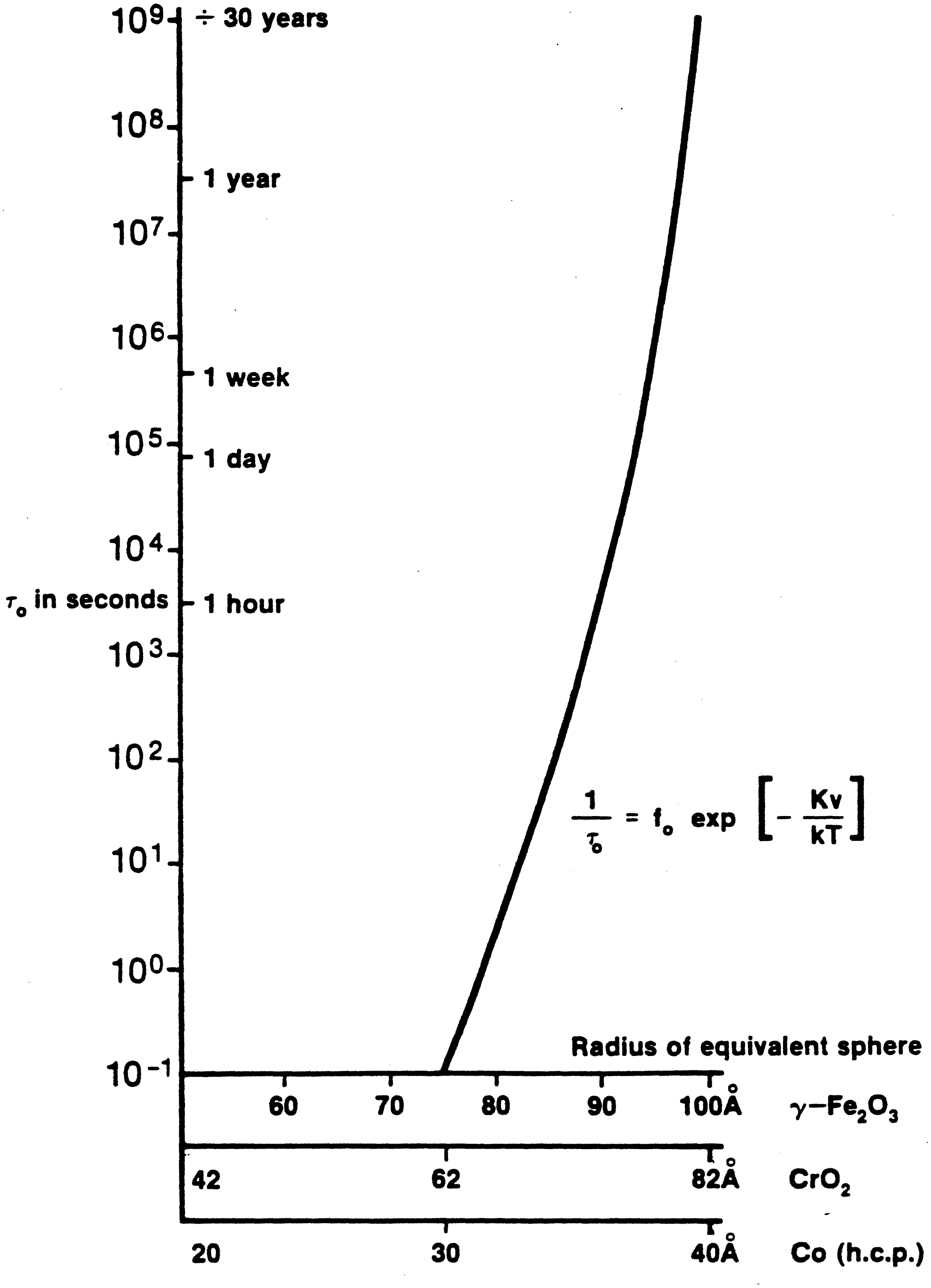
Hard	High Ms	High Hc	High Mr
$\gamma-Fe_2O_3$	400	300-450	200-300
$BaO.6Fe_2O_3$	360	2000-3000	180
$SmCo_5$	700	24,000	700
$Fe_{14}BNd_2$	400	41,000	430



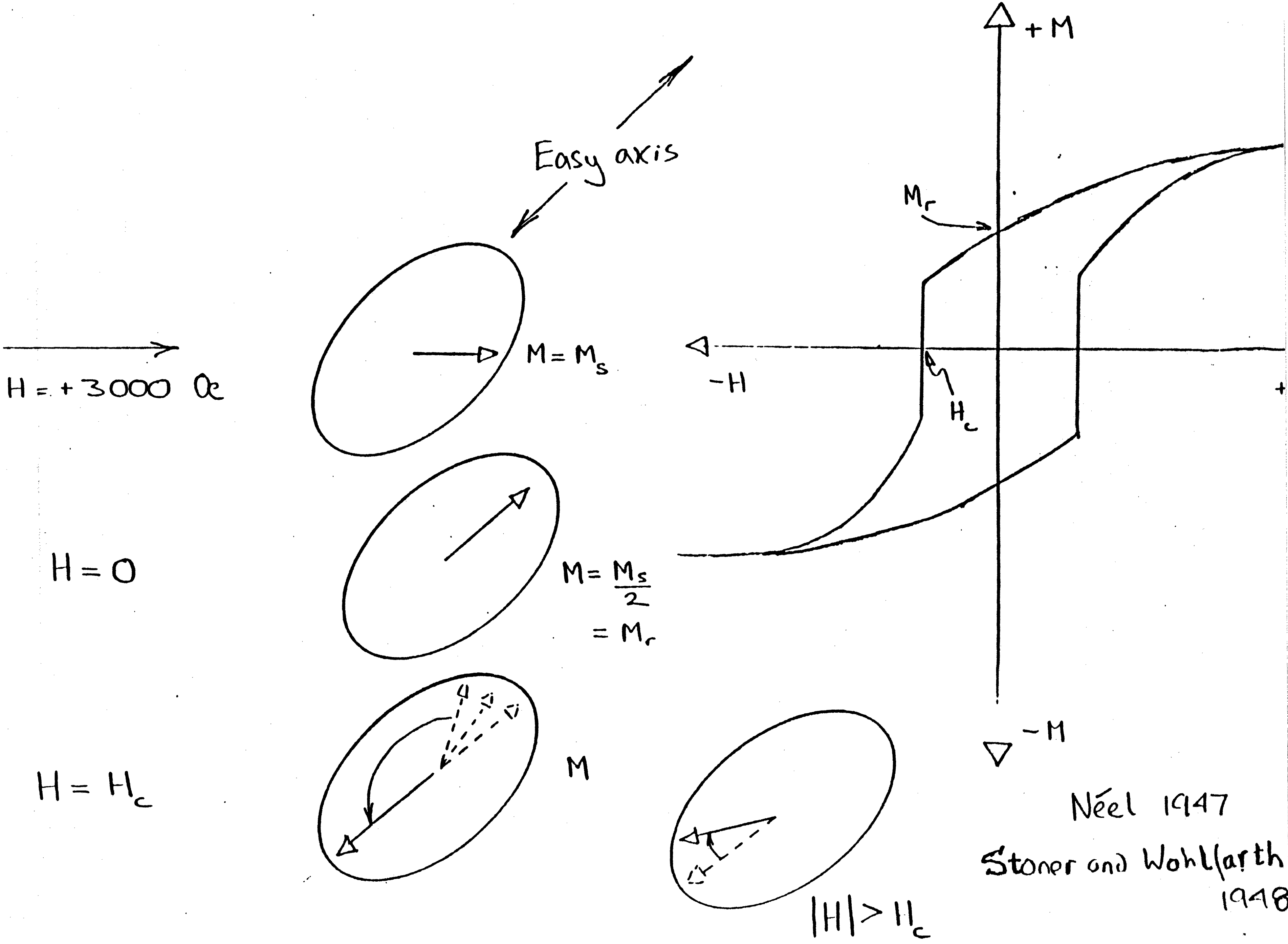


	Multi-Domain	**Single Domain**	**Superparamagnetic**
coercivity:	Hc < 100 Oe	Hc = 100 – 3000	Hc = 0
Ms	400 – 1700 emu/cc	400 – 1700	400 – 1700
$\frac{M_r}{M_s}$	< 0.5	$0.5 < \frac{M_r}{M_s} < 1.0$	0
			

RELAXATION TIME FOR ACICULAR PARTICLES



SHAPE ANISOTROPY $\theta = 45°$

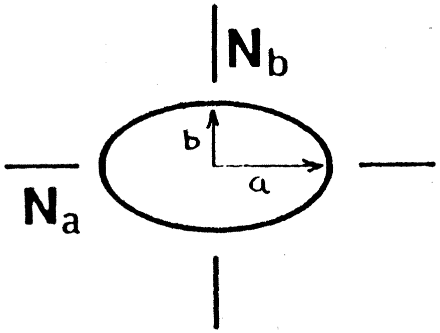


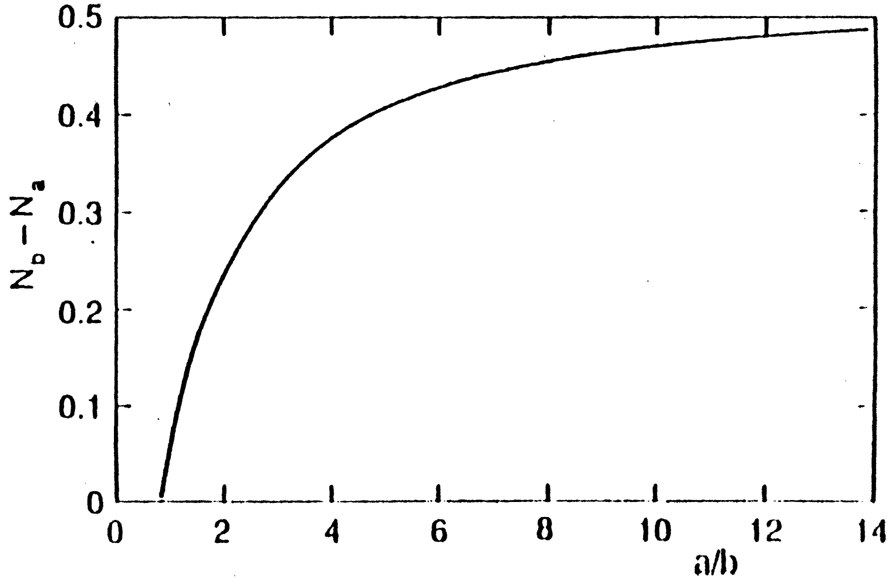
Néel 1947

Stoner and Wohlfarth 1948

SINGLE DOMAIN PARTICLES

Anisotropy	Maximum Coercivity
Crystalline	$H_c = \frac{2\,k_1}{M_s}$
Strain	$H_c = \frac{3\,\lambda_s T}{M_s}$
Shape	$H_c = (N_b - N_a)\,M_s$





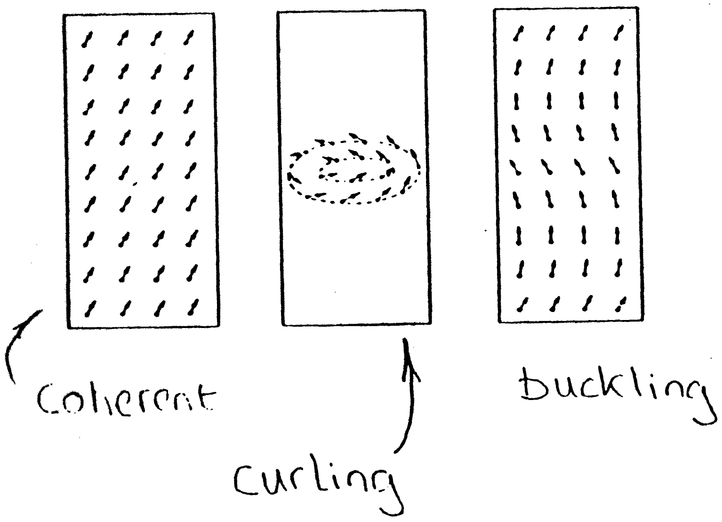
SINGLE DOMAIN PARTICLES

Maximum Coercivity

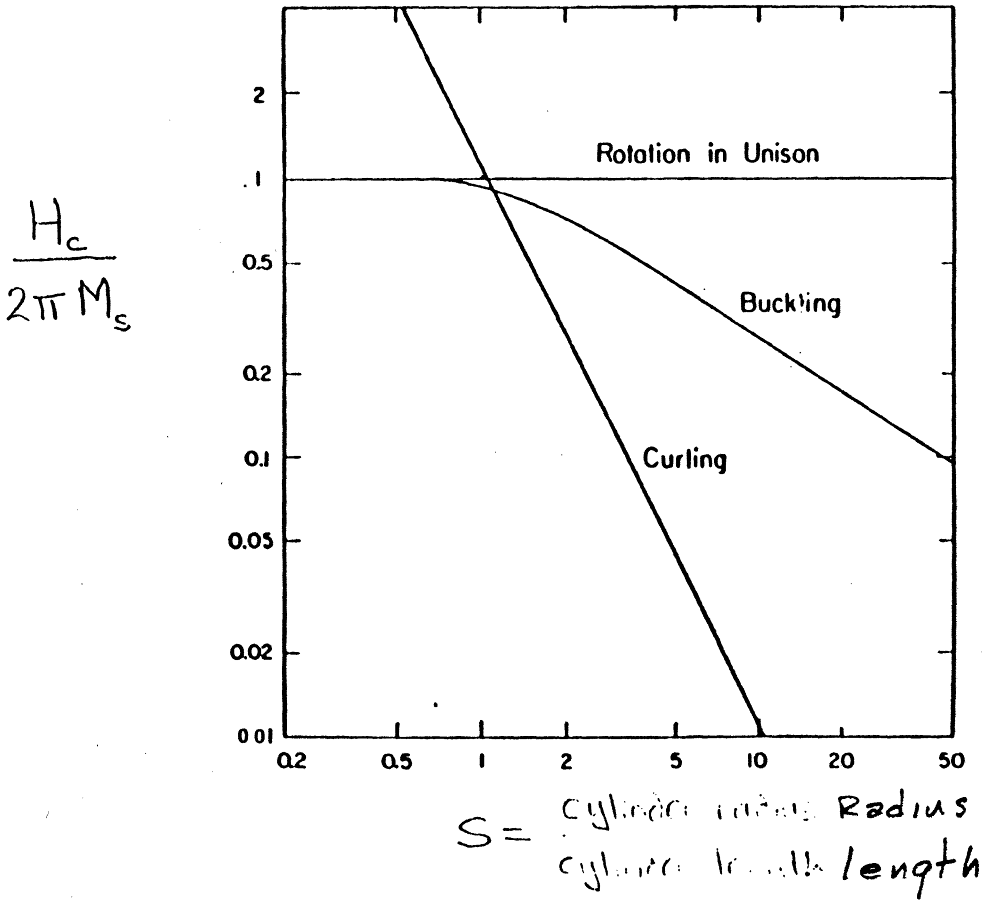
TEMPERATURE DEPENDANT

	Iron	Cobalt	Nickel	$\gamma-Fe_2O_3$
Crystalline	250	3,000	70	230
Strain	300	300	2,000	<10
Shape (10:1)	5,300	4,400	1,550	2,450

INCOHERENT MAGNETIZATION REVERSAL



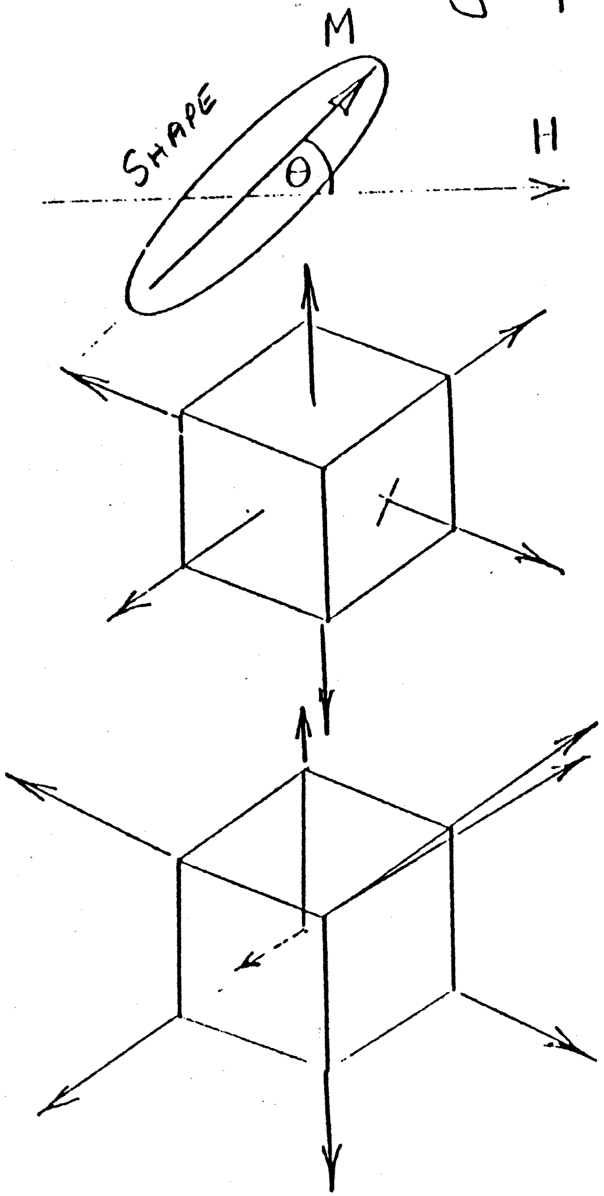
infinite cylinders



GR

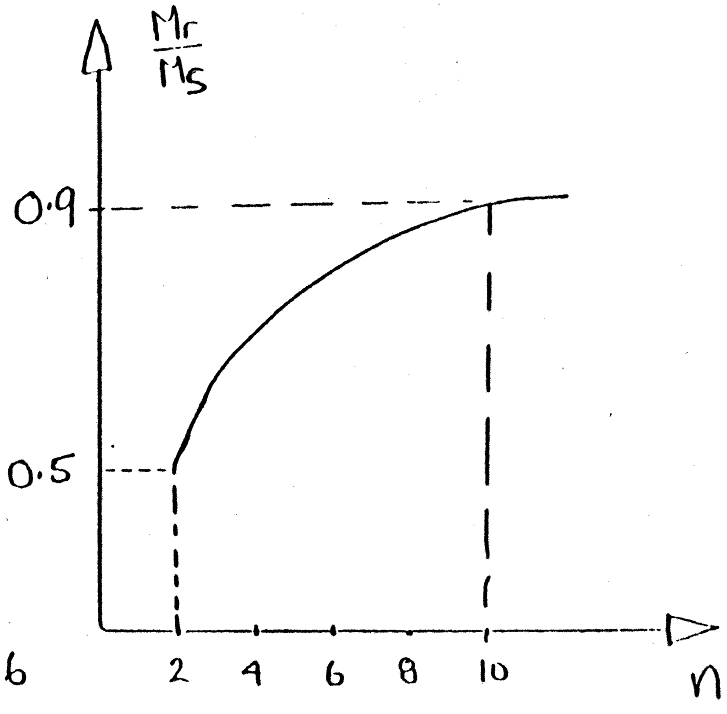
REMANENCE AND PARTICLE ALIGNMENT

'random' assembly of uniaxial particles.



$n = 2$ = number of equivalent easy directions

$$\frac{M_r}{M_s} = 0.5$$



$n = 6$, $\frac{M_r}{M_s} = 0.825$

easy axes <100>

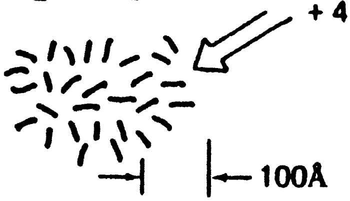
$n = 8$, $\frac{M_r}{M_s} = 0.86$

easy axes <111>

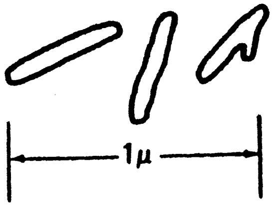
Acicular $\gamma - Fe_2O_3$

Step 1 Preparation of colloidal $\alpha - (FeO)OH$ – goethite

$$4FeSO_4 \cdot 7H_2O + O_2 + 8NaOH \rightarrow 4\alpha - (FeO)OH + 4H_2SO_4 + 30H_2O$$



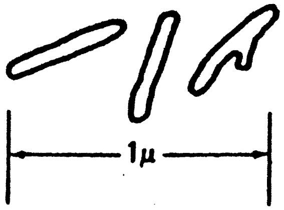
Step 2 use these as seeds to grow larger crystals of $\alpha - (FeO)OH$ with water, scrap iron, air, 60°C, 4 hours.



$\alpha - (FeO)OH$.
Yellow crystals

Step 3 Dehydrate

$$2\alpha - (FeO)OH \xrightarrow{230 - 270^\circ C} \alpha - Fe_2O_3 + H_2O$$



Hematite red crystals

Step 4 Reduce

$$3\alpha - Fe_2O_3 + H_2 \xrightarrow{H_2,\ 300-400^\circ C} 2Fe_3O_4 + H_2O$$

Magnetite black crystals

Pores caused by evolution of oxygen

Step 5 Carefully re-oxidize

$$4\,Fe_3O_4 + O_2 \xrightarrow{\sim 200^\circ C} 6\gamma \cdot Fe_2O_3$$

Maghemite red-brown crystals

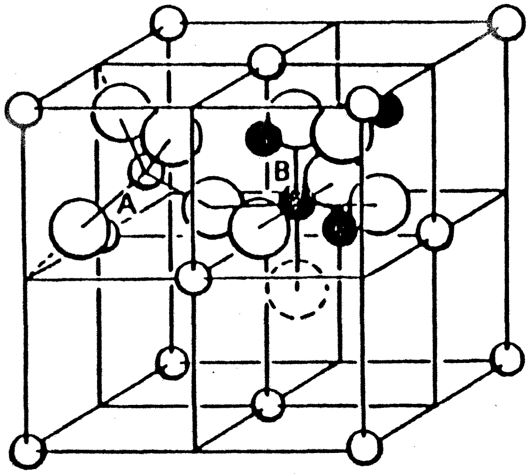
Transformations

Pigment → dehydrated oxide → magnetite → maghemite

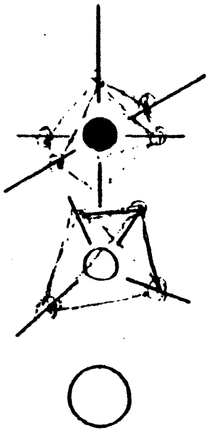
$[\alpha-(FeO)OH]$ $[\alpha-Fe_2O_3]$ $[Fe_3O_4]$ $[\gamma-Fe_2O_3]$

– are Pseudomorphic

INTRINSIC MAGNETIC PROPERTIES OF FE_3O_4 AND γ-FE_2O_3



SPINEL STRUCTURE

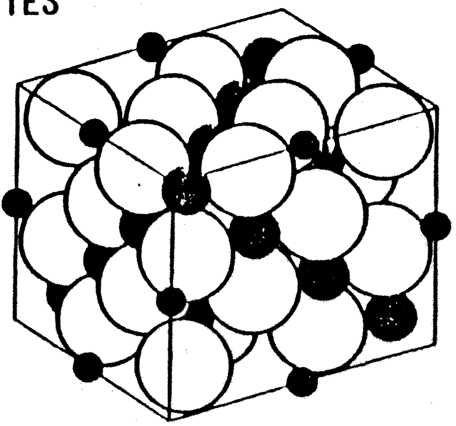


INVERSE SPINEL

FE^{2+} AND FE^{3+} OCTAHEDRAL SITES

FE^{3+} . TETRAHEDRAL SITES

OXYGEN



OCTAHEDRAL SITES = 16 , TETRAHEDRAL SITES = $(8 \times \frac{1}{8}) + (6 \times \frac{1}{2}) + 4 = 8$

Magnetite — inverse spinel

Fe^{3+}	$[Fe^{2+}\ Fe^{3+}]O_4$
A-sites	B-sites
(tetrahedral)	(octahedral)

γ — Ferric Oxide — same oxygen sublattice

— vacancies arranged on a tetragonal superlattice (c/a = 3)

$$Fe_8 \left[\left(Fe_{1\frac{1}{3}}\Delta_{2\frac{2}{3}}\right) Fe_{12}\right] O_{32}$$

is the formula for $\frac{1}{3}$ unit cell.

	Fe_3O_4	$\gamma - Fe_2O_3$
Moment per molecule	4β	2.5β
σ_{so}	97 emu/g	82 emu/g
σ_s	87 emu/g	74 emu/g
Density	5.197 g/cc	5.074 g/cc
I_s	453 emu/cc	400 emu/cc
Curie temperature	575°C	590°C
Anisotropy constant		
	$K_1 = -1.10 \times 10^5$ erg/cc	$= -4.64 \times 10^4$ erg/cc
	⟨111⟩ easy	⟨110⟩ easy
	⟨100⟩ hard	⟨100⟩ hard

INTRINSIC PROPERTIES: γ-Fe_2O_3, Fe_3O_4

$\boxed{Fe_3O_4}$

"INVERSE SPINEL"

A SITES	B SITES		
Fe^{3+}	Fe^{2+}	Fe^{3+}	O_4
$\longrightarrow$	$\longleftarrow$	$\longleftarrow$	
$5\mu_B$	$4\mu_B$	$5\mu_B$	

NET MOMENT = $\boxed{4\mu_B}$ PER FORMULA UNIT

$\sigma_0 = \dfrac{\overset{N\mu_B}{5585}}{\underset{\text{molec. wt}}{M}} n_B$; M = 231.6. ∴ σ_0 = 97 EMU/G (EXPT = 94 EMU/G)

$\boxed{\gamma\text{-}Fe_2O_3}$

more stable

Fe_8^{3+}	$(Fe^{3+}_{4/3}\ \ \Delta_{8/3})$	Fe^{3+}_{12}	O_{32}
$\longrightarrow$	$\longleftarrow$	$\longleftarrow$	
$(8 \times 5)\mu_B$	$(4/3 \times 5)\mu_B$	$(12 \times 5)\mu_B$	

NET MOMENT = $(16/3 \times 5)\mu_B$ per Fe_2O_3

MOMENT PER FORMULA UNIT = $3/32 \times 16/3 \times 5\mu_B = \boxed{2.5\,\mu_B}$

OR 1.25μ /IRON ATOM: EXPT = 1.18

σ_0 = 82 EMU/G

$\underset{R.T.}{\sigma_{\cancel{0}}}$ = 74 EMU/G ; EXPERIMENT

FERRIMAGNETISM

Substance	Lattice parameter a(A)	Density (g cm^3)	0 K		20 C		T_c (C)
			σ_0 (emu/g)	M_0 (emu/cm^3)	σ_s (emu/g)	M_s (emu/cm^3)	
$MnO \cdot Fe_2O_3$	8.50	5.00	112	560	80	400	300
$FeO \cdot Fe_2O_3$	8.39	5.24	98	510	92	480	585
$CoO \cdot Fe_2O_3$	8.36	5.29	90	475	80	425	520
$NiO \cdot Fe_2O_3$	8.34	5.38	56	300	50	270	585
$CuO \cdot Fe_2O_3$	8.37*	5.41	30	160	25	135	455
$MgO \cdot Fe_2O_3$	8.36	4.52	31	140	27	120	440
$BaO \cdot 6Fe_2O_3$	a = 5.88 c = 23.2	5.28	100	530	72	380	450
Fe	2.87	7.87	222	1747	218	1714	770

$MgO \cdot Fe_2O_3$

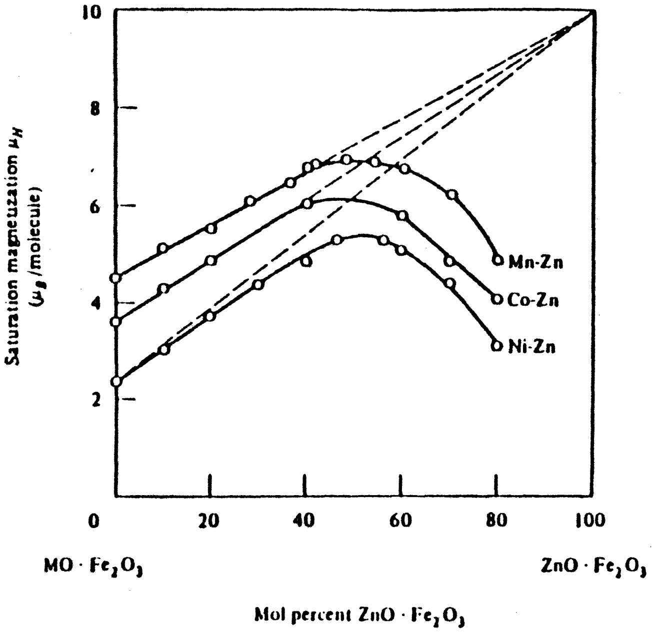
(pure inverse $\Rightarrow n_{\mu_B} = 0$)

$\left.\begin{array}{l} 0.1 \text{ of } Mg^{2+} \\ 0.9 \text{ of } Fe^{3+} \end{array}\right\}$ A sites

$0.9 \times 5 = 4.5 \mu_B$

$\left.\begin{array}{l} 0.9 \text{ of } Mg^{2+} \\ 1.1 \text{ of } Fe^{3+} \end{array}\right\}$ B sites

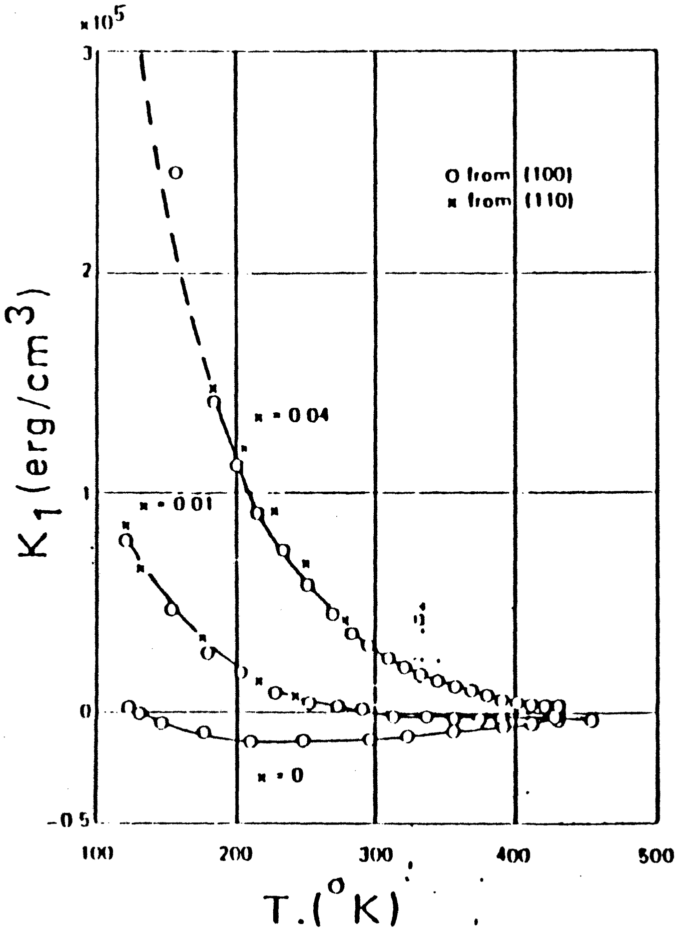
$1.1 \times 5 = 5.5 \mu_B$



Example	Substance	Structure	Tetrahedral A sites	Octahedral B sites	Net moment (μ_B molecule)
1	$NiO \cdot Fe_2O_3$	Inverse	Fe^{3+} 5 →	Ni^{2+}, Fe^{3+} 2 5 ← ←	2
2	$ZnO \cdot Fe_2O_3$	Normal	Zn^{2+} 0	Fe^{3+}, Fe^{3+} 5 5 ← →	0
3	$MgO \cdot Fe_2O_3$	Mostly inverse	Mg^{2+}, Fe^{3+} 0 4.5 →	Mg^{2+}, Fe^{3+} 0 5.5 ←	1
4	$0.9\ NiO \cdot Fe_2O_3$	Inverse	Fe^{3+} 4.5 →	Ni^{2+} Fe^{3+} 1.8 4.5 ← ←	
	$0.1\ ZnO \cdot Fe_2O_3$	Normal	Zn^{2+} 0	Fe^{3+} Fe^{3+} 0.5 0.5 ← ←	
			4.5 →	7.3 ←	2.8

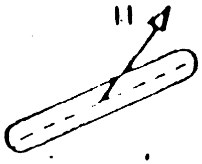
Cobalt — Modified Iron Oxides

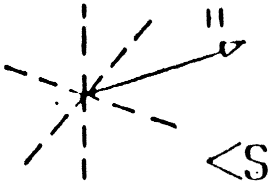
Cobalt substitution



$Co_xFe_{3-x}O_4$

Bickford et al. (1957)

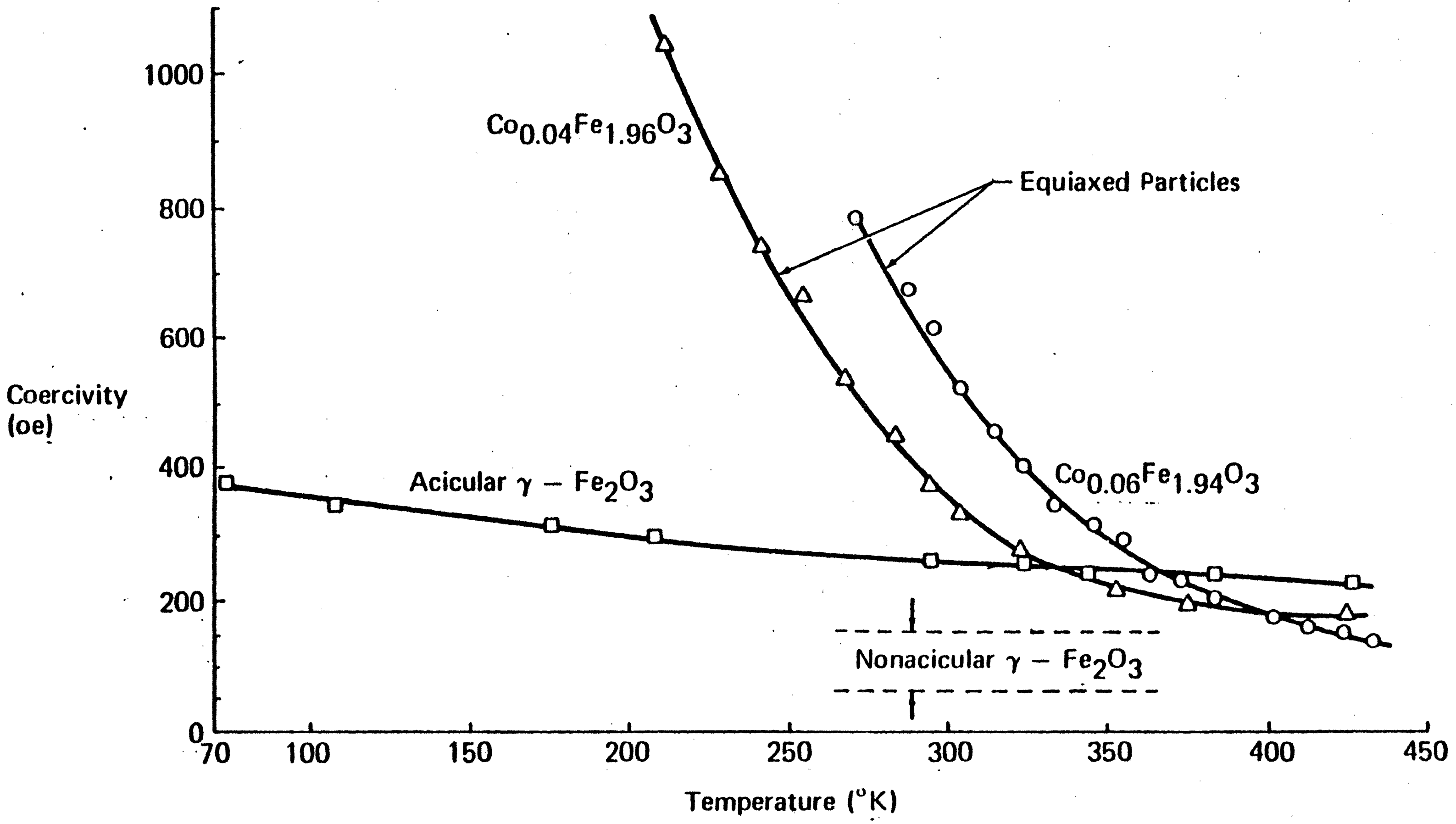
- $H_c = 0.64 \frac{K_1}{M_s}$, temperature sensitive
- 

$\langle S \rangle = 0.5$


$\langle S \rangle = 0.825$
- Remanence, time and stress dependent

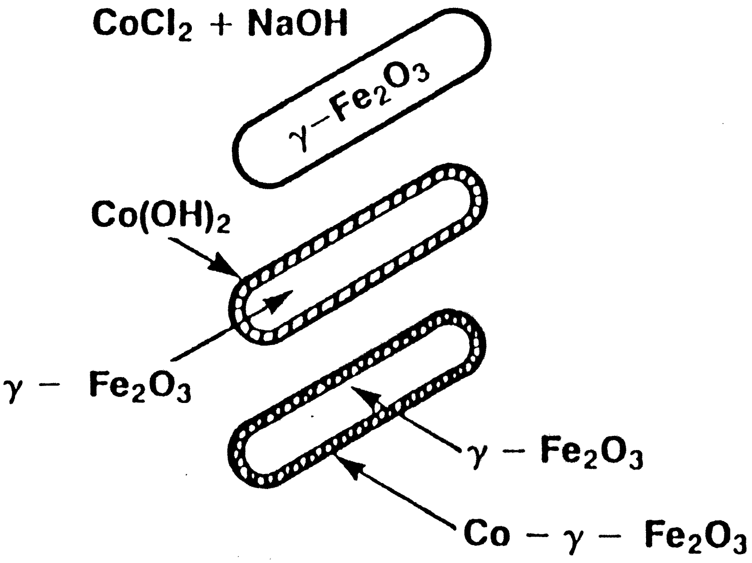
3/11/82

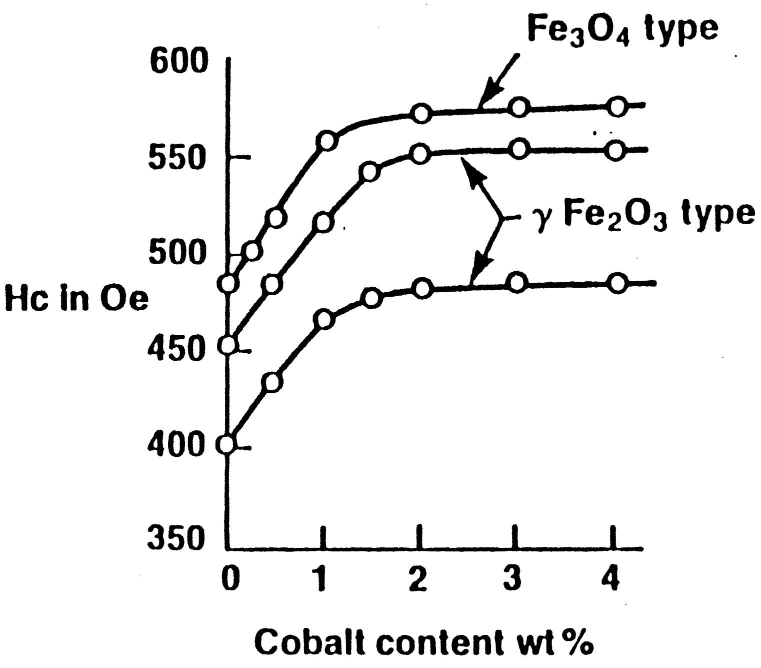
Bate



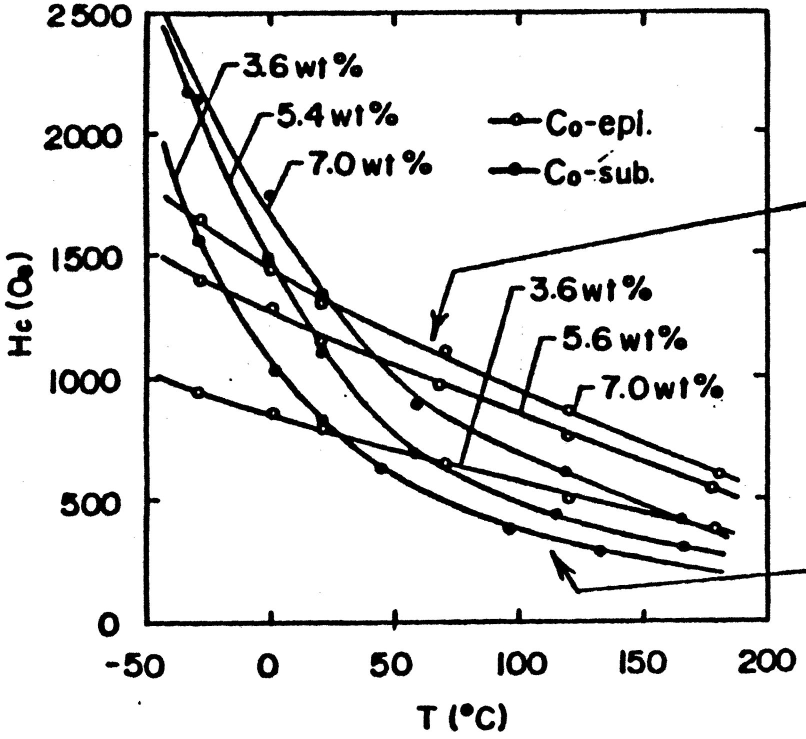
$Co_{0.04}Fe_{1.96}O_3$
Equiaxed Particles
$Co_{0.06}Fe_{1.94}O_3$
Acicular $\gamma - Fe_2O_3$
Nonacicular $\gamma - Fe_2O_3$
Coercivity (oe)
1000
800
600
400
200
0
70
100
150
200
250
300
350
400
450
Temperature (°K)

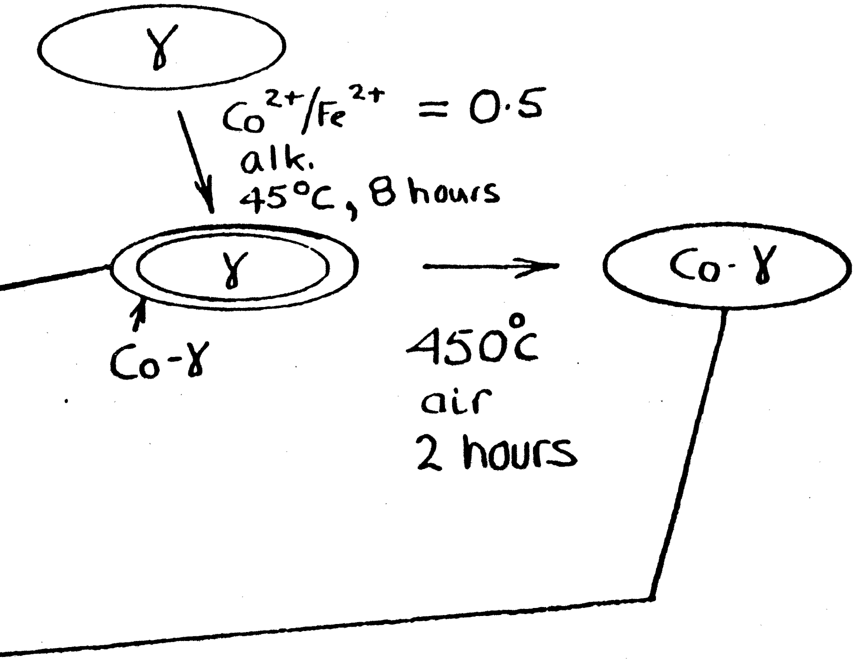
COBALT-IMPREGNATED IRON OXIDE

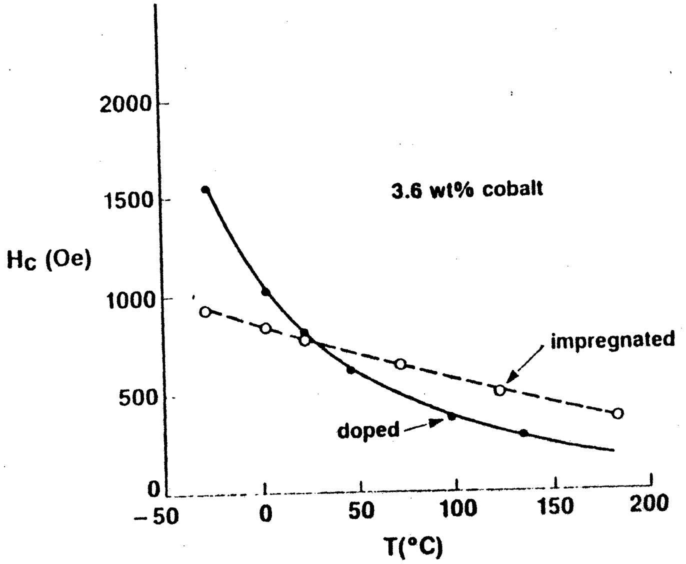




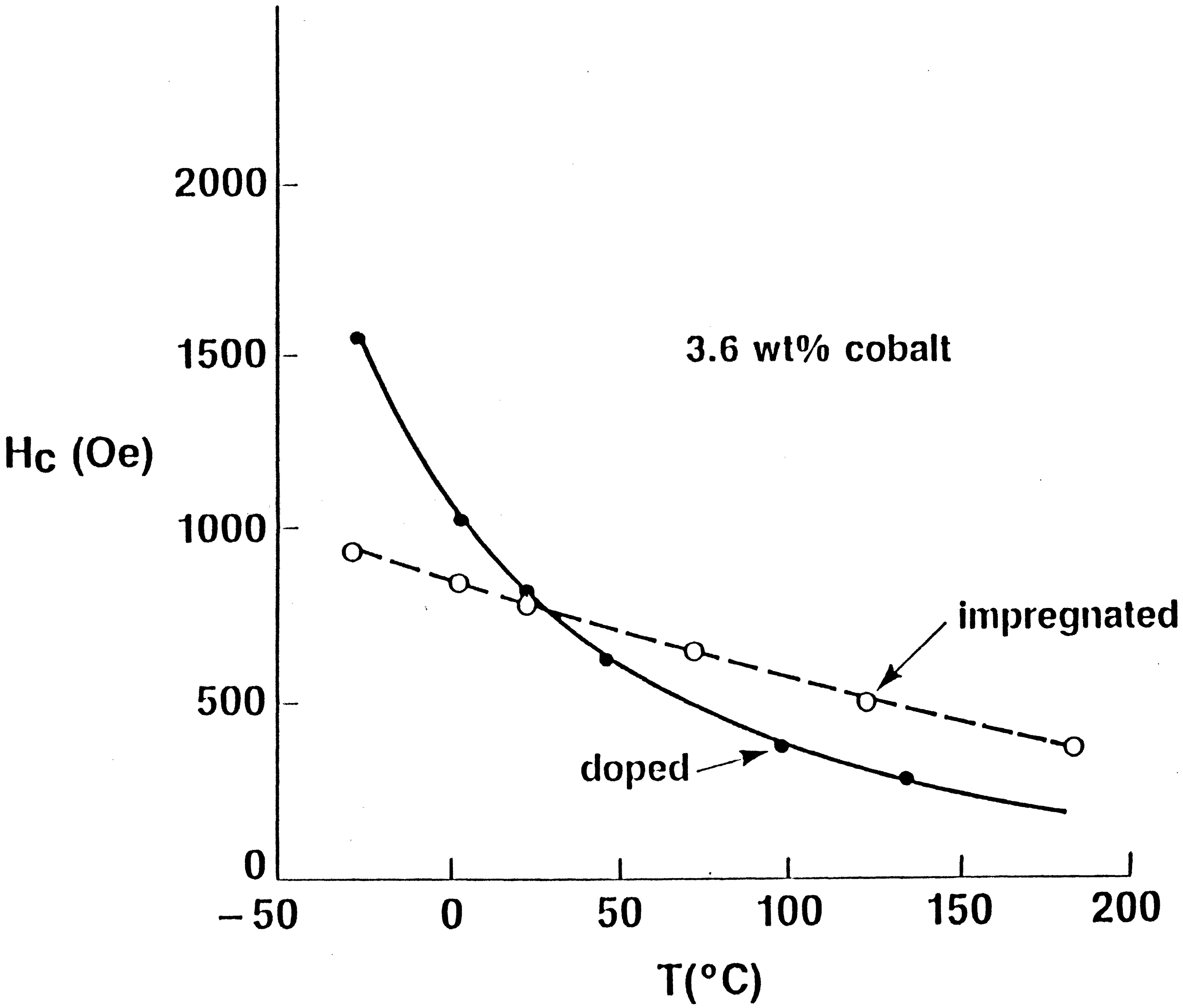
COBALT - MODIFIED γ-Fe_2O_3 PARTICLES

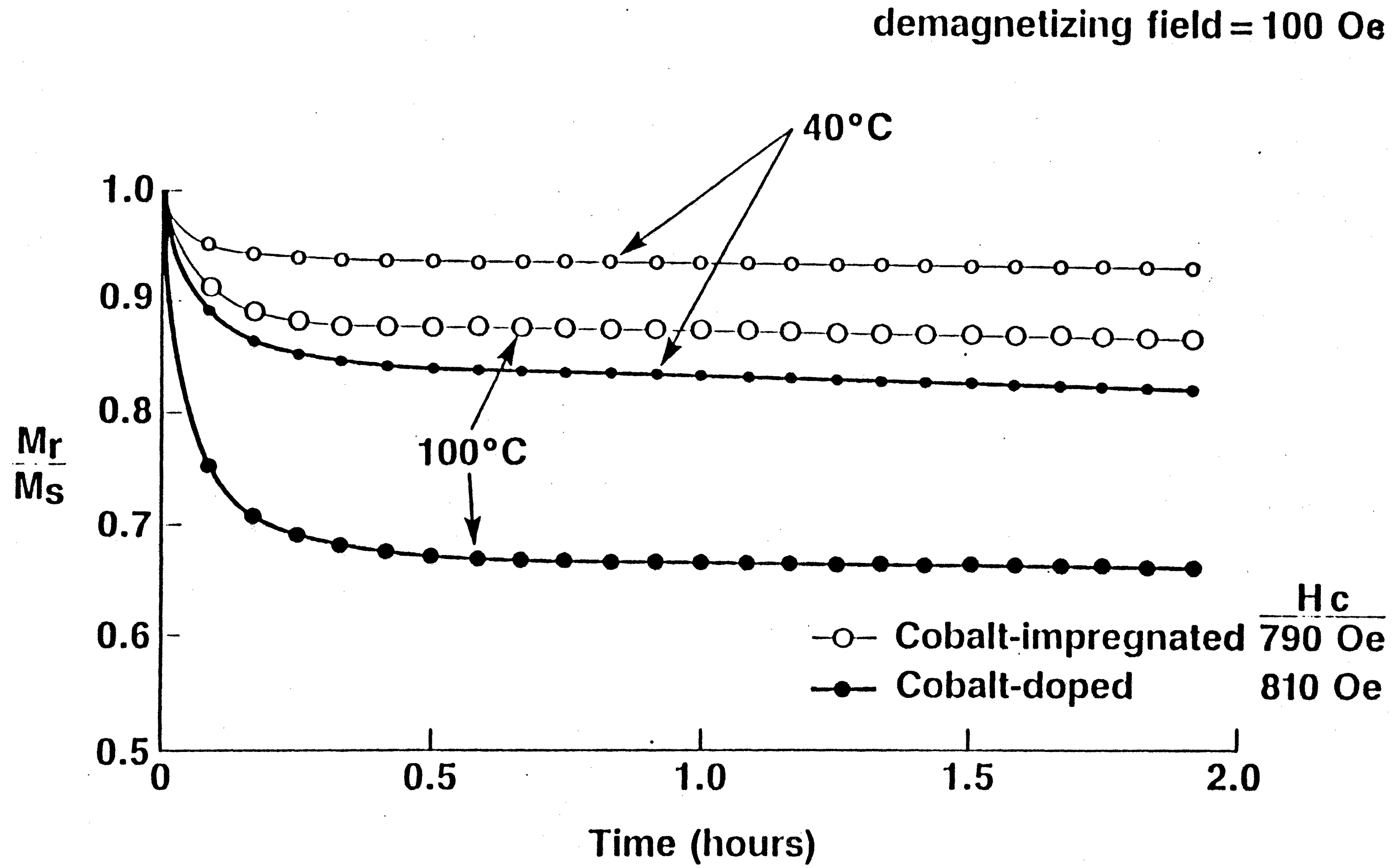




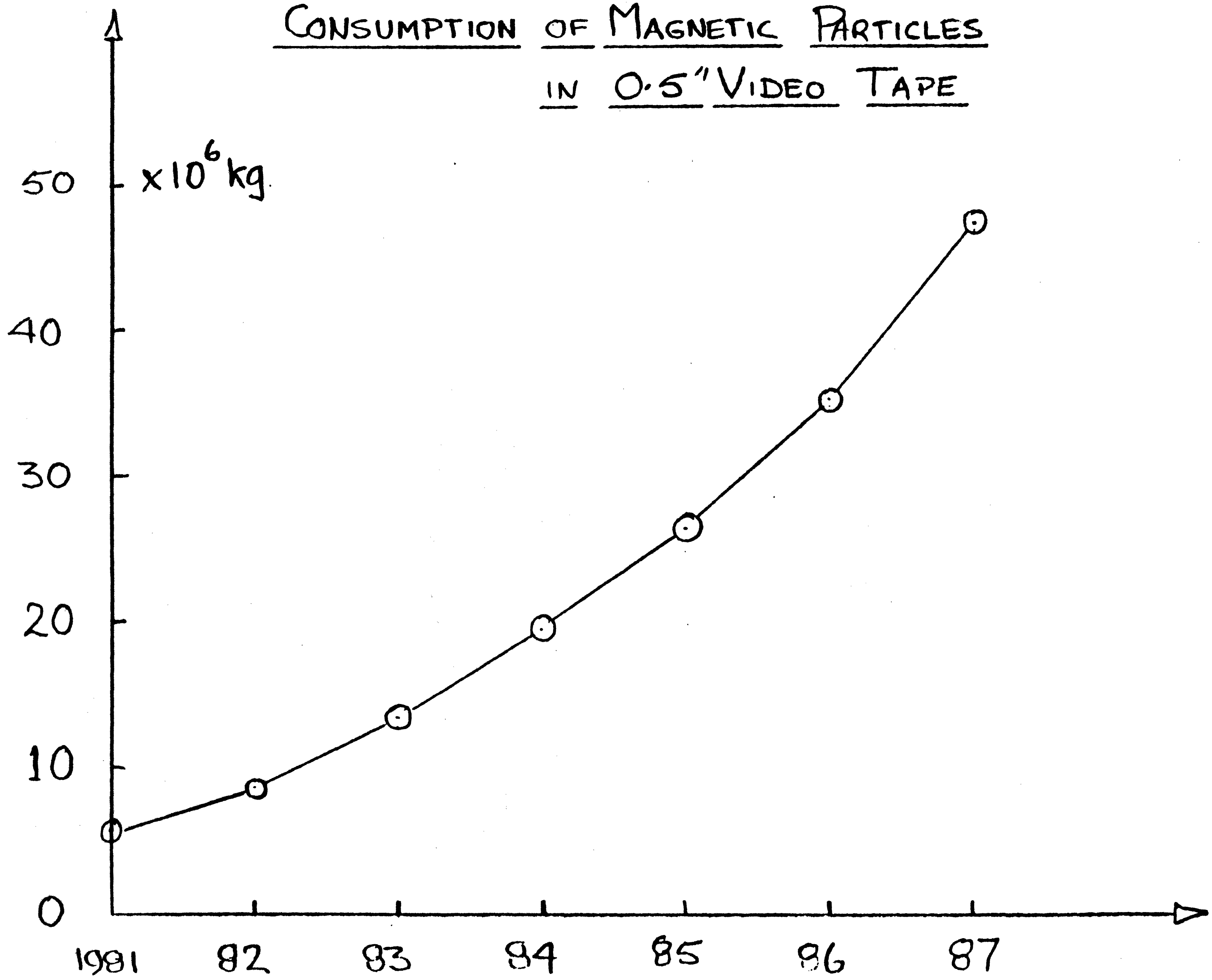


([illegible]hi to, Amemiya, [illegible]ma).


3.6 wt% cobalt
Hc (Oe)
2000
1500
1000
500
0
-50
0
50
100
150
200
T(°C)
impregnated
doped


demagnetizing field = 100 Oe
40°C
100°C
Mr/Ms
1.0
0.9
0.8
0.7
0.6
0.5
0
0.5
1.0
1.5
2.0
Time (hours)
Hc
—○— Cobalt-impregnated 790 Oe
—●— Cobalt-doped 810 Oe

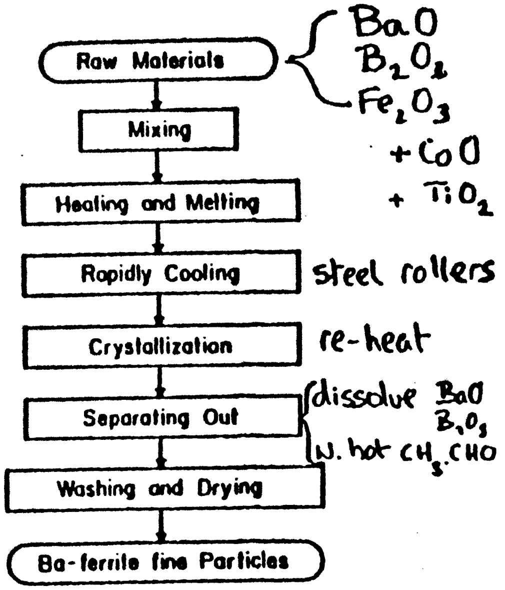
CONSUMPTION OF MAGNETIC PARTICLES IN 0.5" VIDEO TAPE



SOURCE: MMIS, p25 November 1983

Particle / Property	γ-Fe_2O_3	Co-Fe_2O_3	CrO_2	BaO.6 Fe_2O_3 + Co, Ti	Fe	Fe_4N
σ_s saturation magnetization, emu/g	73-74	73-76.3	70-80	45-70	150-190	110-130
$\frac{\sigma_r}{\sigma_s}$	0.5	0.5-0.8	0.5	0.6-0.7	0.23-0.52	0.47-0.53
Curie Temperature, T_c,°C	[590]	[590]	115-126	320	768	490
magnetocrystalline anisotropy constant, K_1, ergs/cc	-4.64×10^4	$-5\ r_o + 100 \times 10^4$	$+2.5 \times 10^5$	$+3.3 \times 10^6$	$+4.4 \times 10^5$	
saturation magnetostriction λ_s	-5×10^{-6}	-5 to -15×10^{-6}	$+1 \times 10^{-6}$		$+4 \times 10^{-6}$	
coercivity, H_c, Oe	250-350	550-750	450-670	320-1970	375-1650	640-1100
switching field distribution, $\frac{\Delta H}{H_c}$	0.26-0.61	0.30-0.6	0.35-0.6	0.16-0.6	0.5-0.75	0.5-0.7
temperature coeff. of coercivity, $\Delta H_c/H_c$/°C (20–70°C)	-1×10^{-3}	Impreg.^{d} -2.4×10^{-3} doped -10×10^{-3}	-5×10^{-3}	$+3.1 \times 10^{-3}$	-0.6×10^{-3}	-0.7×10^{-3}
specific surface area (BET), m^2/g	20-40	20-40	25-37	15-31	26	25-40
density, ρ, g/cc	4.60	4.80	4.80-4.95	5.28	5.8	5.8
crystal structure	cubic $a_0 = 25$ Å, m3m	cubic	tetragonal a = 4.4218 Å c = 2.9182 Å	hexagonal c = 23.2 Å a = 5.88 Å	b.c.c. a = 2.861 Å	f.c.c. a = 3.795 Å
ferro- or ferrimagnetic	ferri	ferri	ferro	ferri	ferro	ferro
particle size, μm	needles l = 0.3 d = 0.06	needles w equimax. l = 0.3 l = 0.2 d = 0.06	needles l = 0.5 d = 0.05	hex. platelets dia = 0.08-0.1 thick = 001-0.025	needles l = 0.3 d = 0.06	l = 0.5 dia = 0.07

PREPARATION AND PROPERTIES OF BARIUM FERRITE PARTICLES

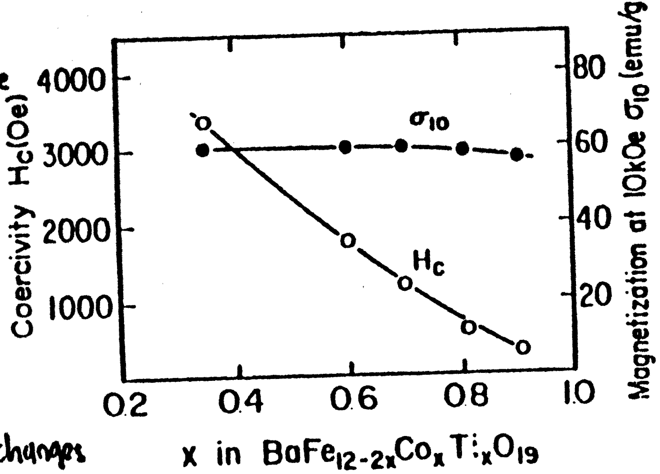


Block diagram showing the Ba-ferrite particle preparation process using the glass crystallization method. → uniform nucleation,
→ small, well-separated, narrow size range

Typical Ba-ferrite fine particles characteristics

Particle size	0.08 x 0.03 μm
Density	5.25 g/ml
Specific surface area	22 m^2/g
Coercivity	900 Oe
Saturation magnetization	58 emu/g
Curie temperature	350°C
Squareness ratio	0.94

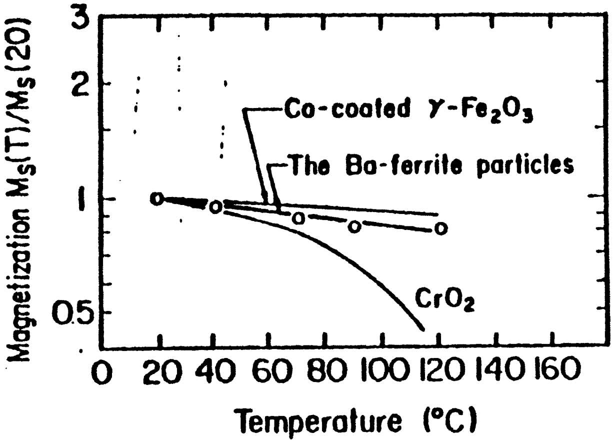
$\langle d \rangle \sim 0.08 \mu m$
$\langle t \rangle \sim 0.03 \mu m$

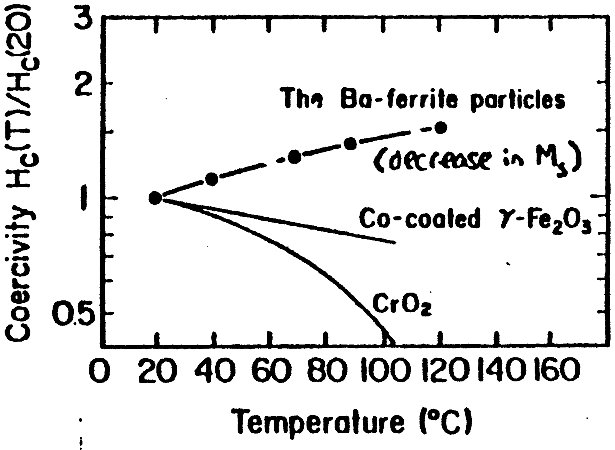


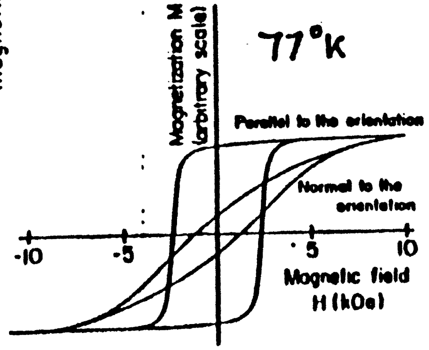
- Co, Ti allow control of H_c w/o changes in d, t.
- easy axis // c-axis.

$$H_c = 0.48\left(\frac{2K}{M_s} - NM_s\right)$$

$20°C, x = 0.8 \rightarrow$ 6K oe 4K oe







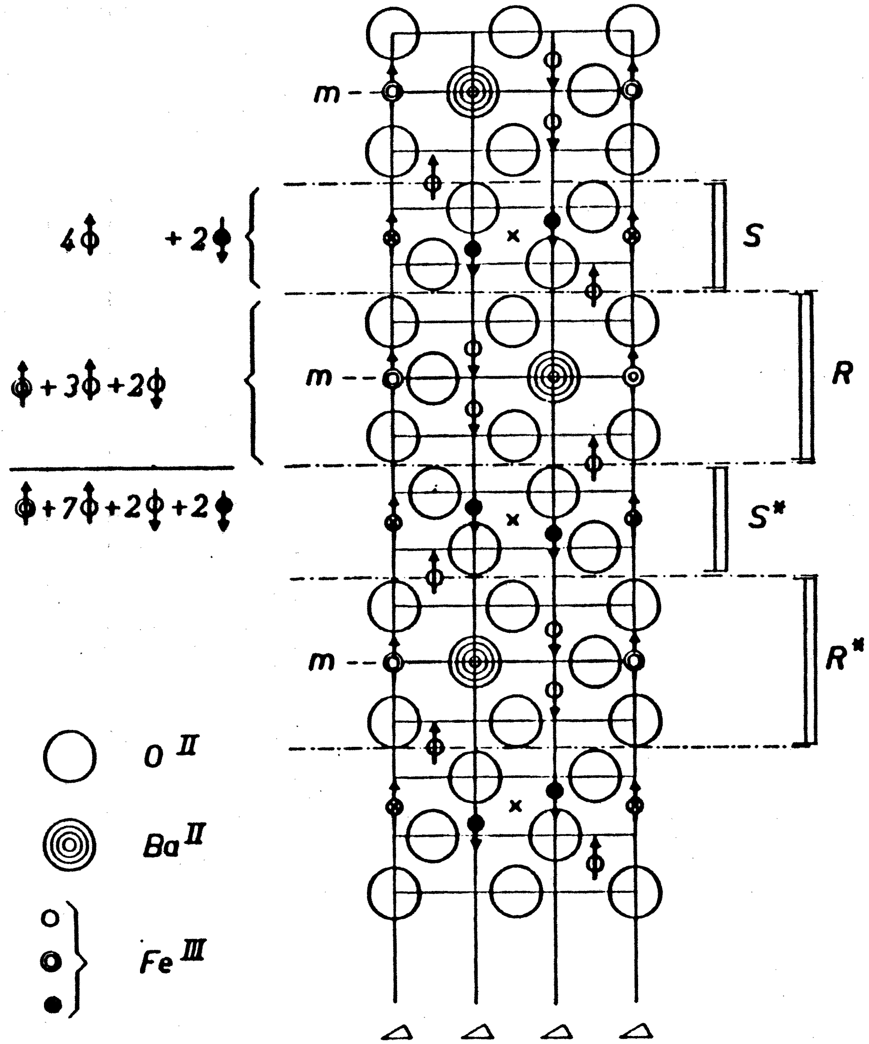
orienting field ≤ 10 K oe

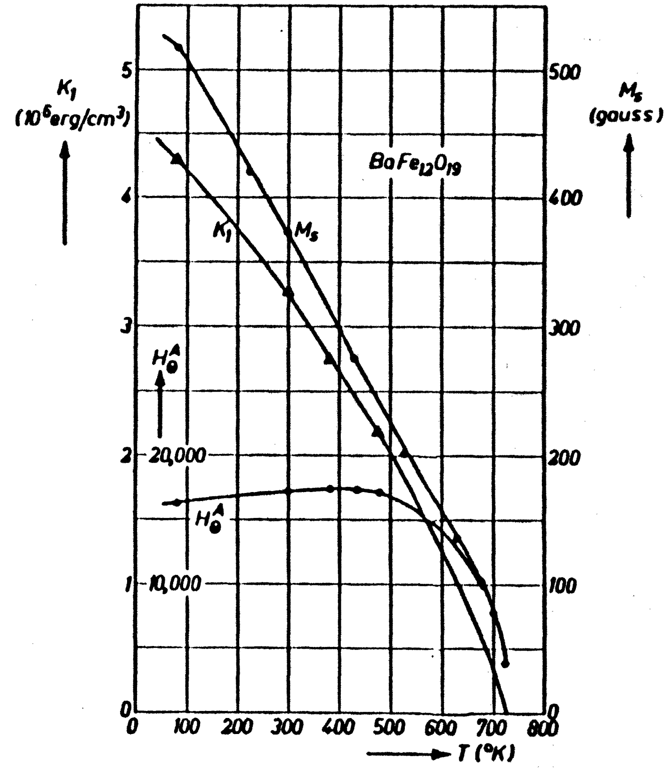
Kubo, l. IEEE Trans. Mag. MAG-18, 1122 (1982)

G. Bat

STRUCTURE AND PROPERTIES OF BARIUM FERRITE

$$BaFe_{12}O_{19} = BaO.6Fe_2O_3$$





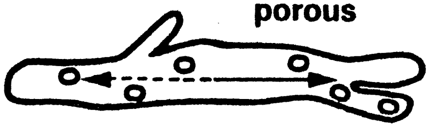
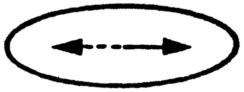
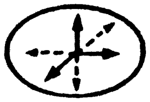
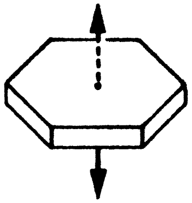
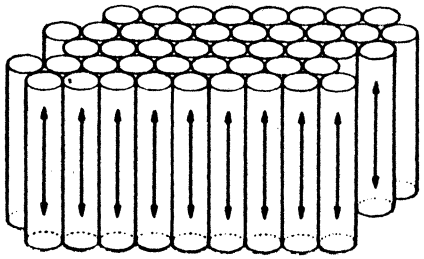
20°C

$M_s = 380$ emu/cc

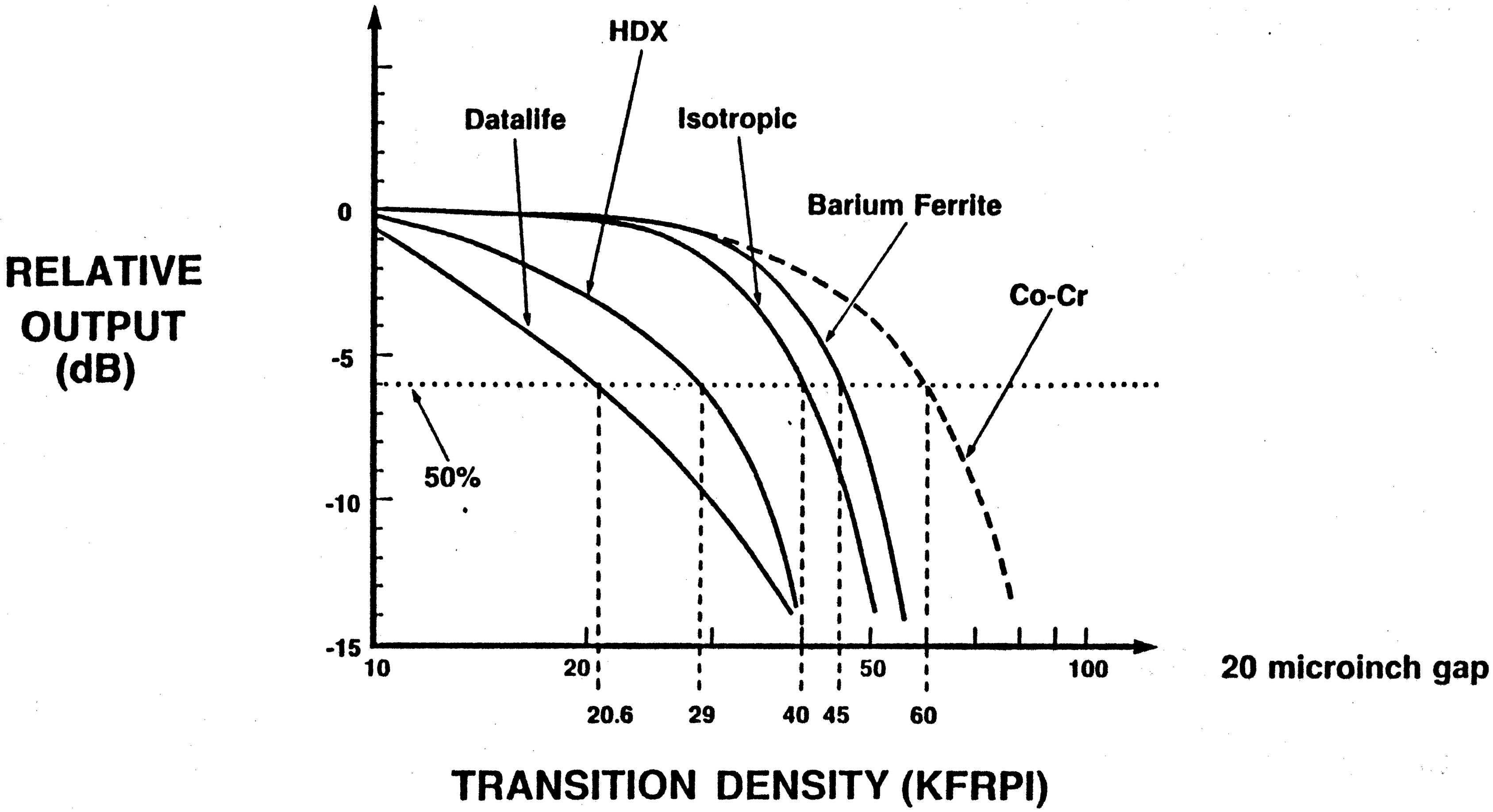
$K_1 = +3.3 \times 10^6$ erg/cc

$H_A = \frac{2K_1}{M_s} \doteq 17{,}000$ Oe

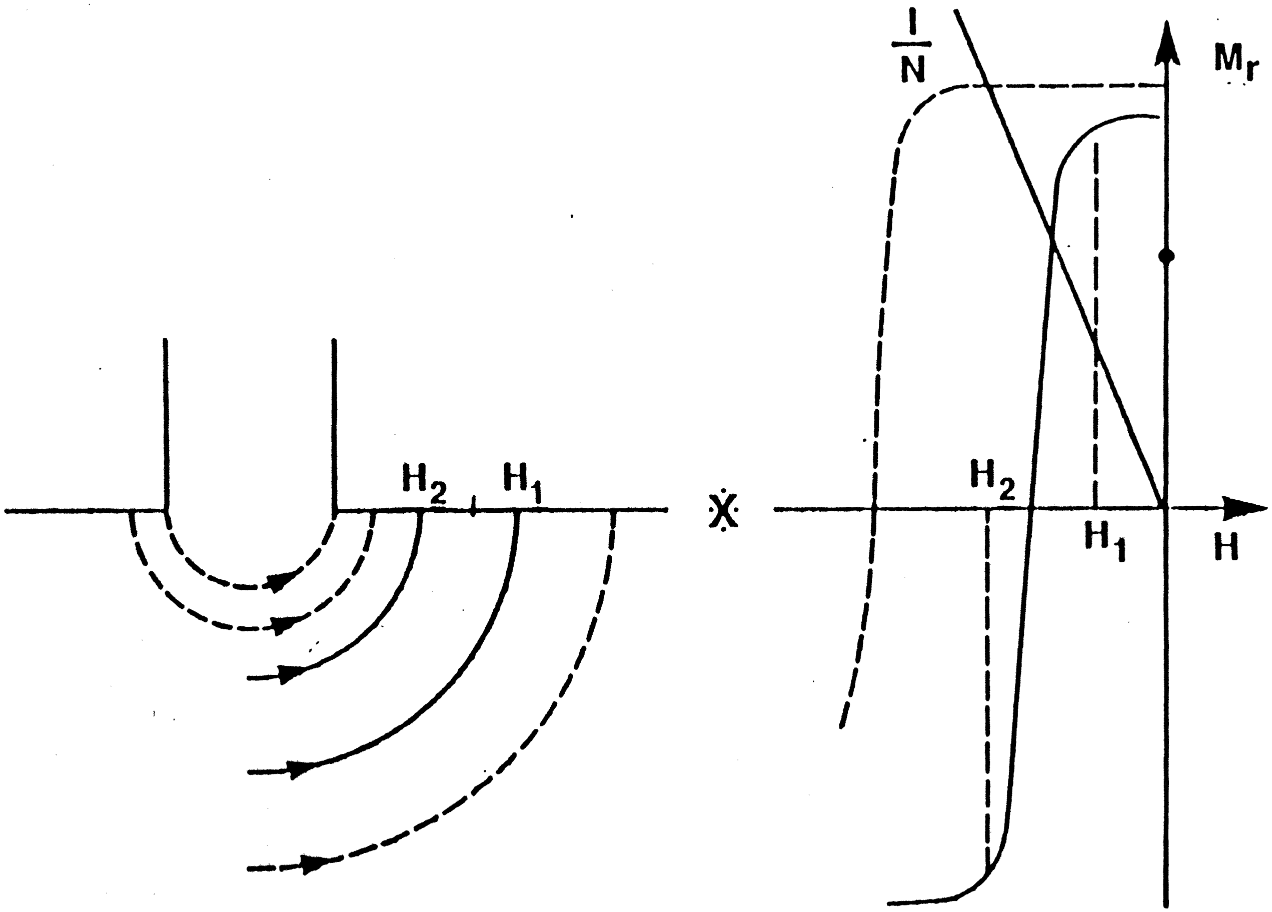
MATERIALS FOR VERY HIGH DENSITY RECORDING

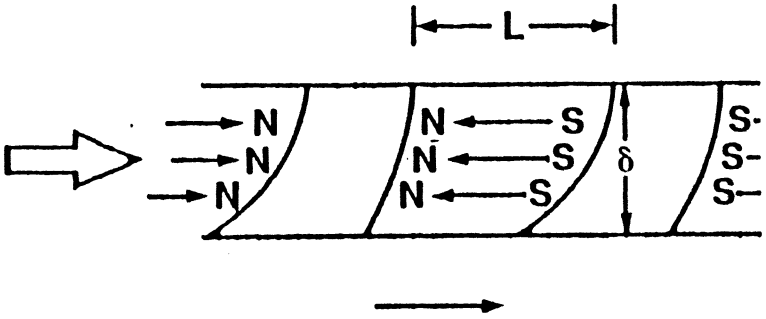
VHD PARTICLES		RECORDING MODE
Conventional Gamma-Iron Oxide (Co-impregnated) Example: HDX particles	 rough, porous	Longitudinal
"Rice Grain" Gamma-Iron Oxide (Co-impregnated)	 smooth, dense	Longitudinal
Isotropic Gamma-Iron Oxide (Co-doped)		Longitudinal/Perpendicular
Barium Ferrite	 hexagonal platelets	Perpendicular
VHD THIN FILMS		
Cobalt - Chrome (sputtered)		Perpendicular

RELATIVE OUTPUT VS. TRANSITION DENSITY



Writing Process





$$H_d = -N\left(\frac{\delta}{L}\right)M_r$$

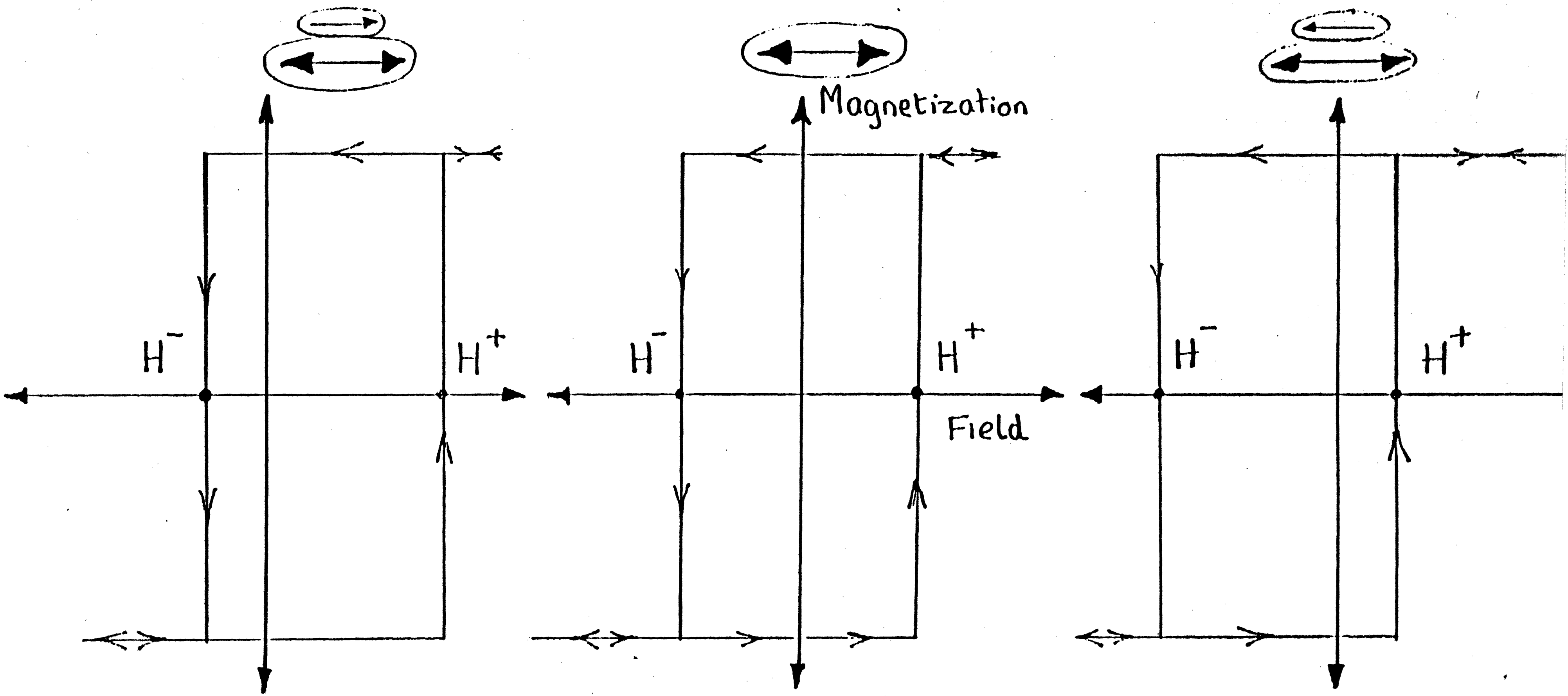
INVERSE OF BIT DENSITY

Bate

PREISACH DIAGRAMS

represent the magnetic interaction between particles in a magnetic tape or disk.

are two-dimensional distribution functions of interaction fields



$H^- < H^+$ $H^- = H^+$ $H^- > H^+$

PREIS CH DIAGRAM

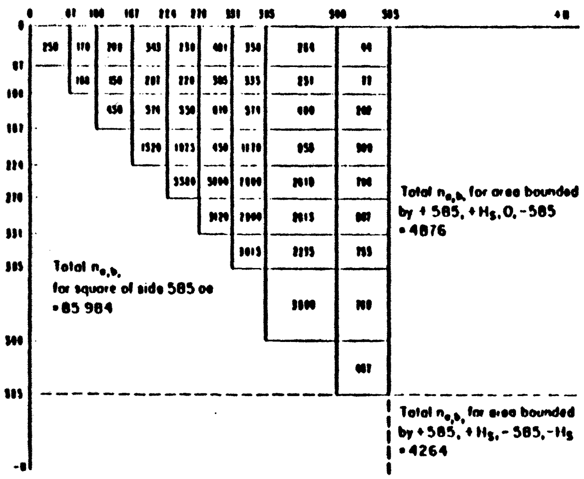


FIG. 6. Part of the Preisach diagram calculated for the nonoriented sample.

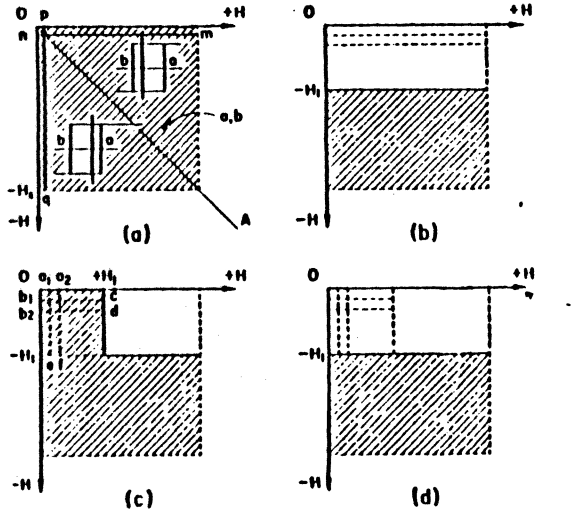


FIG. 1. Preisach diagrams: the shaded area shows the location of particles with positive remanent intensities. Afterfields (a) $+H_s$, the remanence is ${}_sI_r$, (b) $-H_1$, the remanence is ${}_1I_r$, (c) $+H_1$, the remanence is ${}_1I_r'$, (d) $-H_1$, the remanence is ${}_1I_r$.

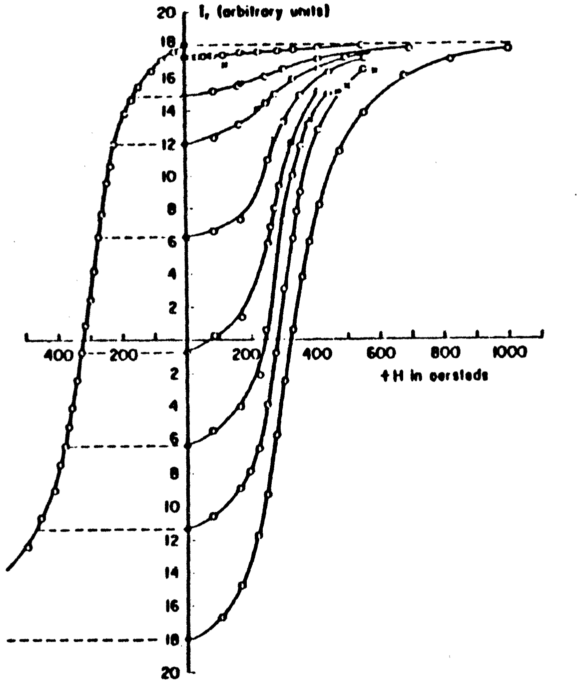
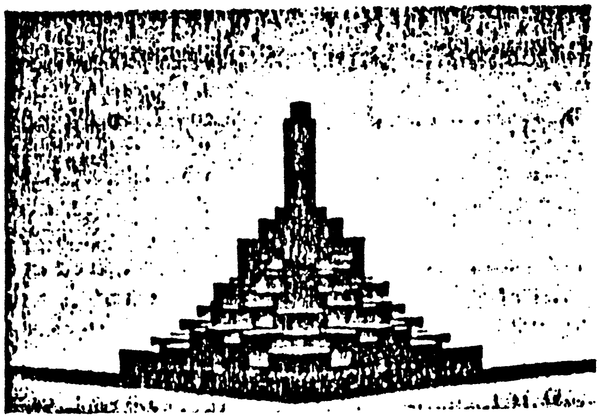
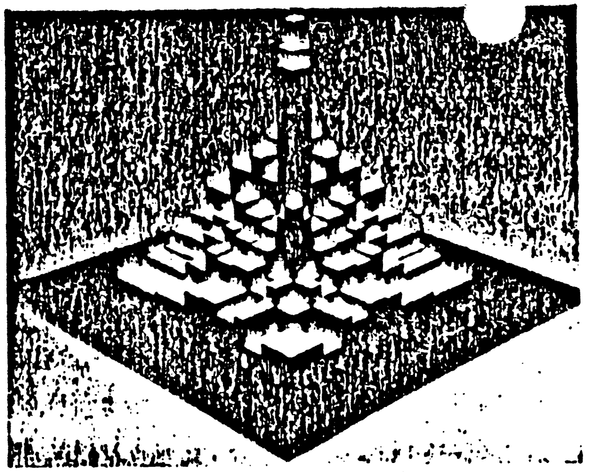
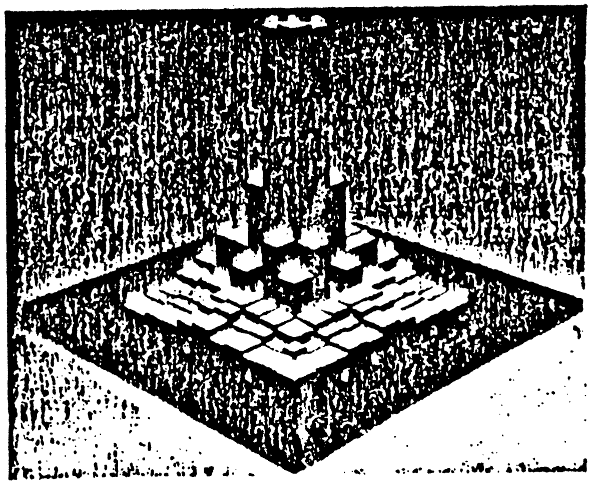
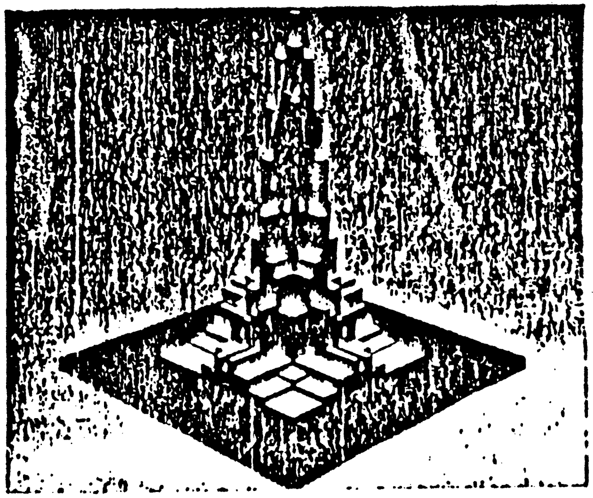


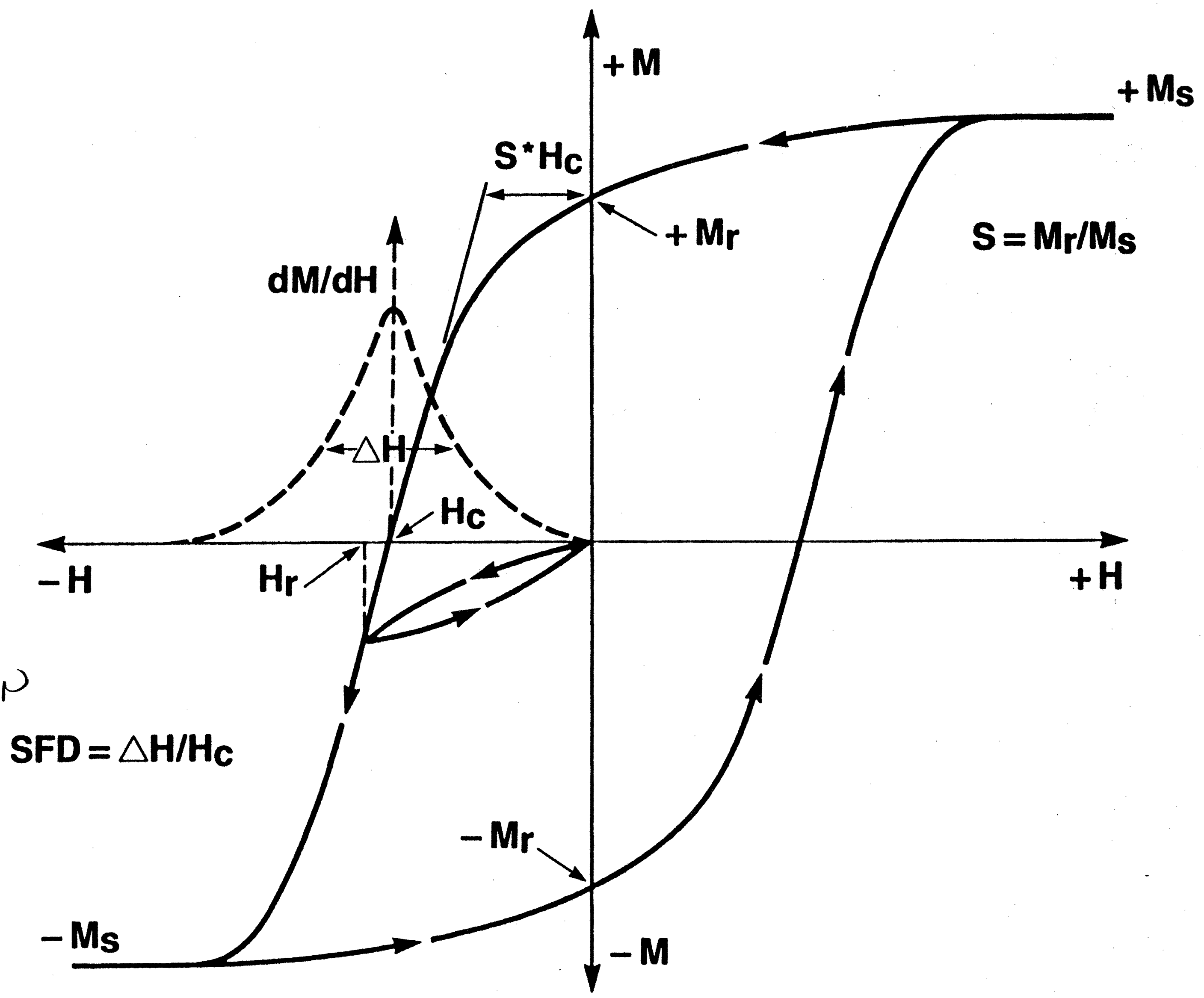
FIG. 2. The descending remanence curve and the ascending curves for the nonoriented sample. The crosses on the ascending curves mark the remanence levels attained after $+H$ when $-H$ was the maximum reverse field for that curve. Some of the curves have been omitted for clarity.





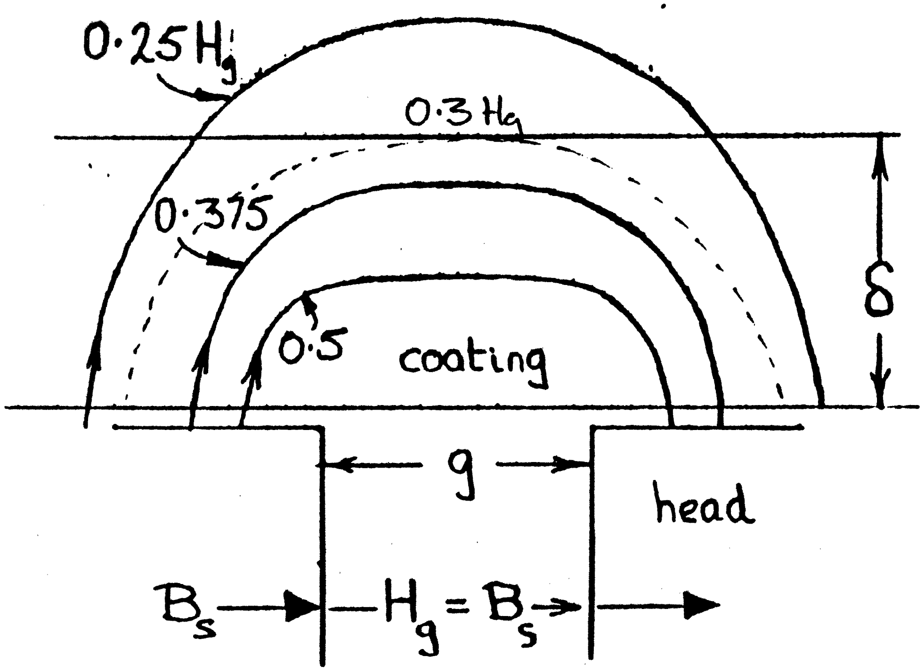






SWITCHING
FIELD
DISTRIBUTION

THE OVERWRITE PROBLEM

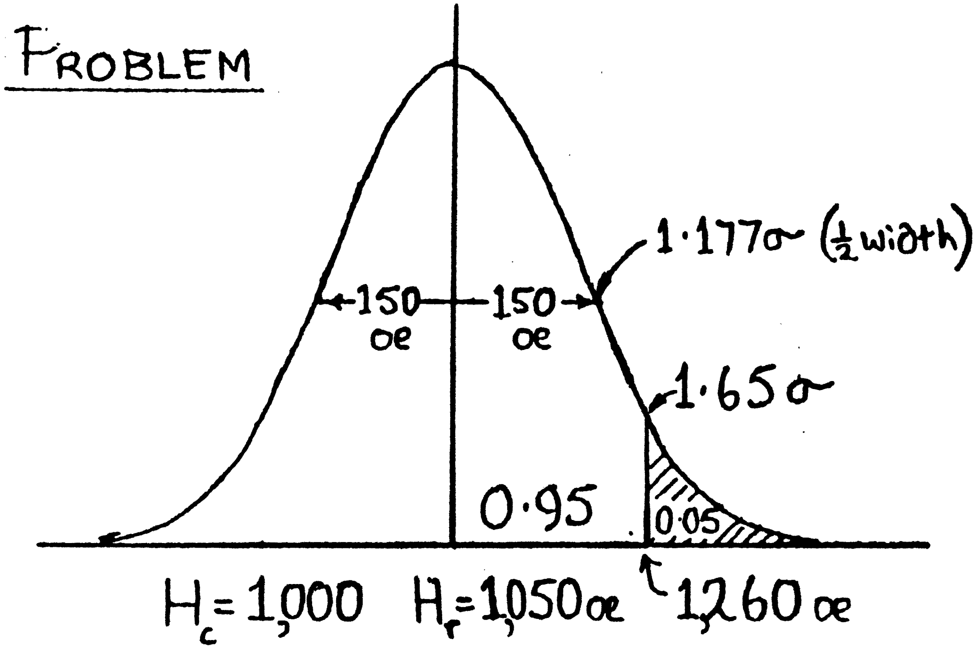


overwrite test:

1) write 1F, measure amplitude
2) overwrite with 2F
3) read remaining 1F amplitude

overwrite criterion: −26dB

$$\frac{\text{remaining 1F}}{\text{original 1F}} \leq 0.05$$



Assumptions: Normal Distribution

$\boxed{S.F.D. = 0.3}$

coating thickness, δ = head gap, g

Result

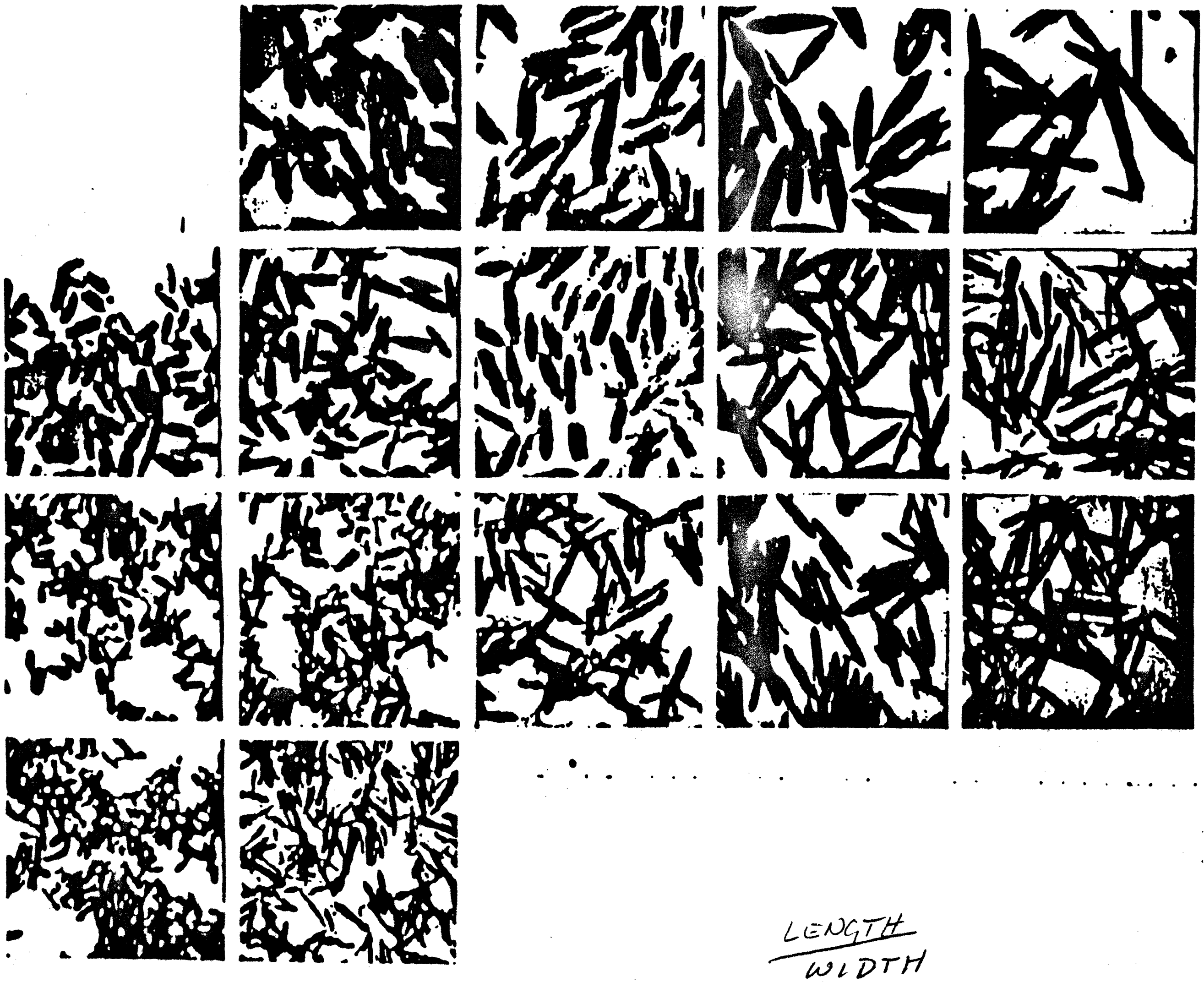
$0.3\,H_g = 1260$

$H_g = 4,200$,

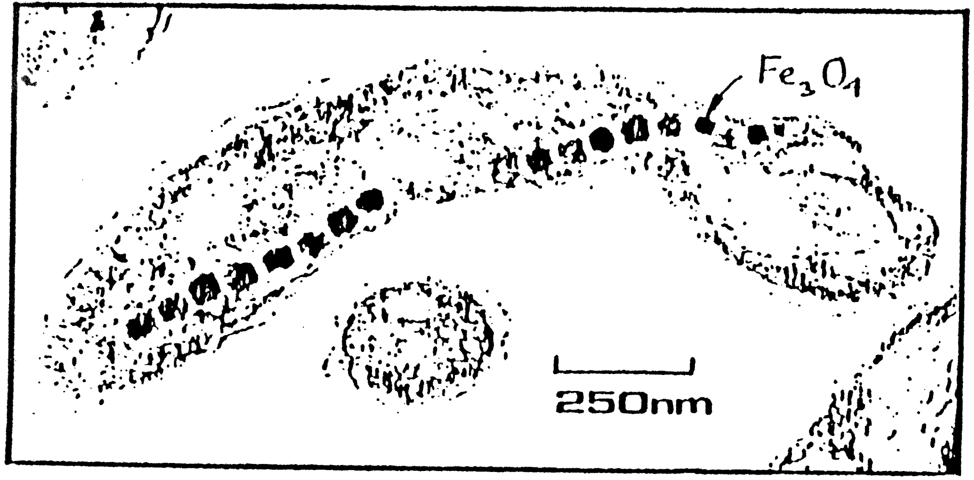
Ferrite	B_s
Ni Zn	4,000
Mn Zn	5,000

G. Bate

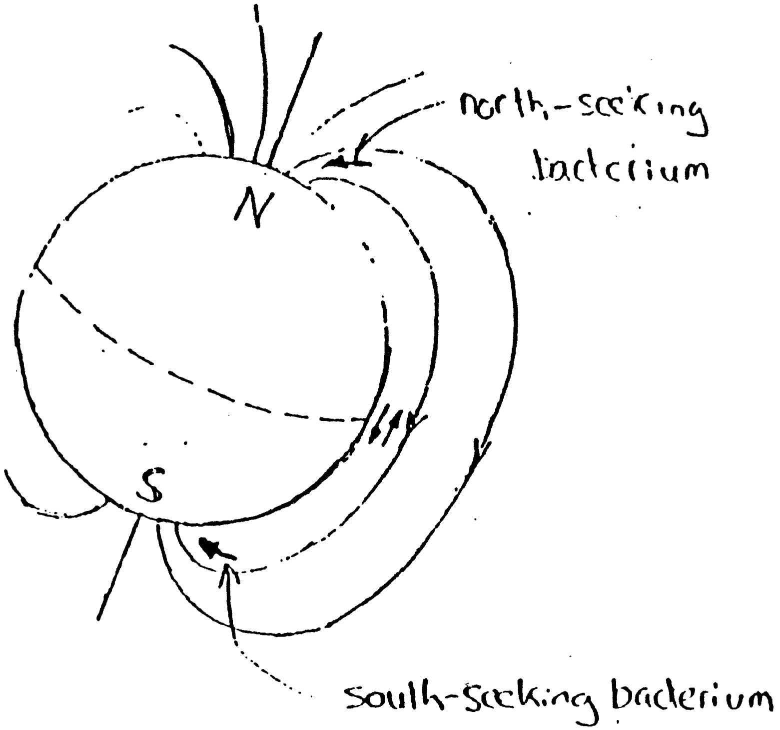
NP Particles



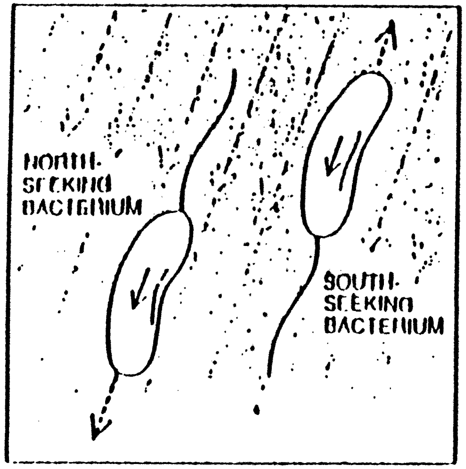
Magnetic Bacteria



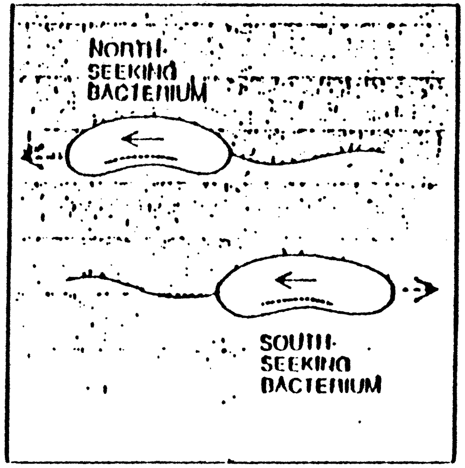
R.B. Frankel 1979



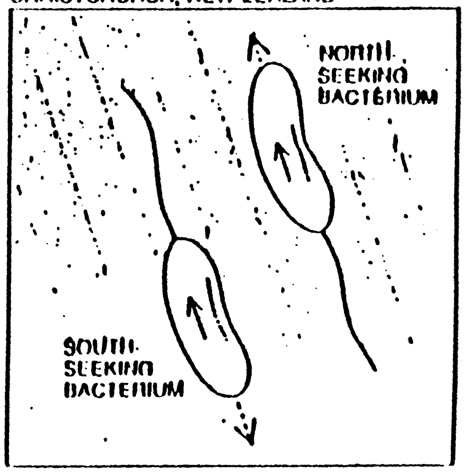
WOODS HOLE, MASS.



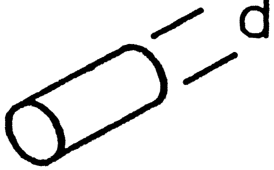
FORTALEZA, BRAZIL



CHRISTCHURCH, NEW ZEALAND



PARTICLE PACKING DENSITY



particle volume $= \frac{\pi d^2}{4} \cdot \ell$

$= 4.24 \times 10^{-15}$ particles cc.

100% packing → 2.3×10^{14} particles/cc.

40% packing → 10^{14} particles/cc.

96 tpi; track width = 5mil $= 1.25 \times 10^{-2}$ cm.

10,000 bpi; bit length $= 10^{-4}$ in. $= 2.5 \times 10^{-4}$ cm.

coating thickness of 40 microinches $= 1.0 \times 10^{-4}$ cm.

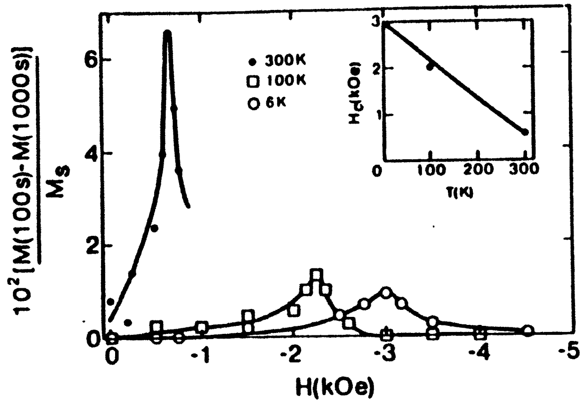
vol. of one bit $= 3.0 \times 10^{-10}$ cc.

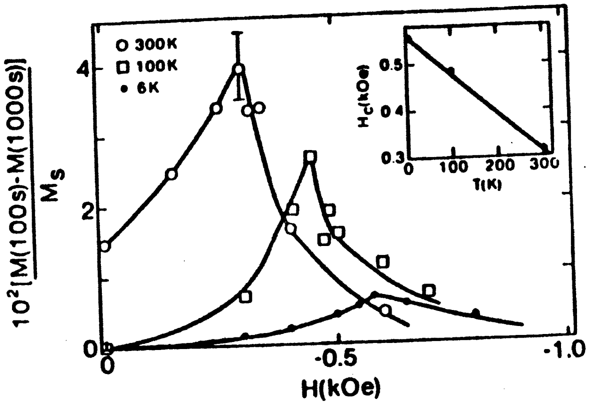
one bit cell contains ~ 30,000 particles

G. Bate

TIME DECAY OF MAGNETIZATION IN MAGNETIC PARTICLES

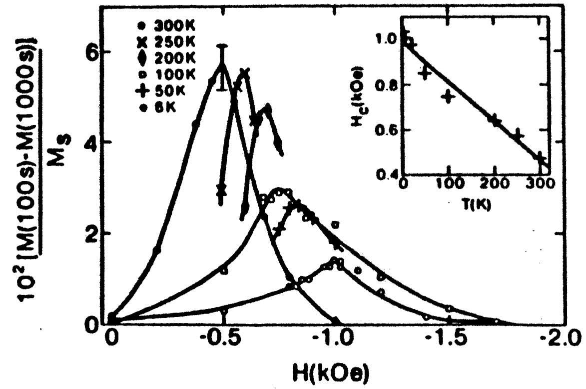
CrO_2

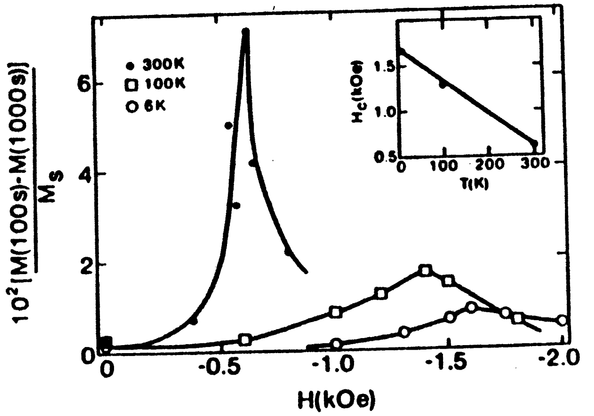




γ-Fe_2O_3

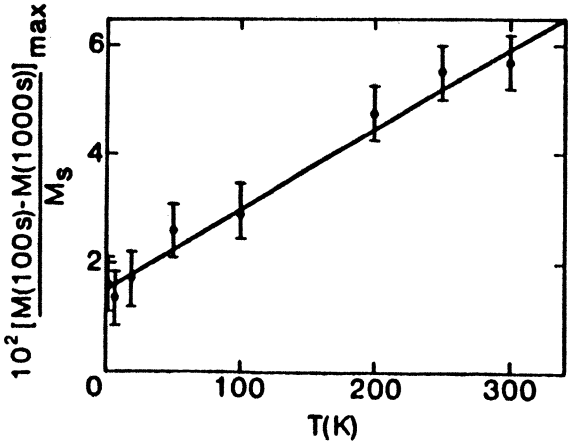
CrO_2





Co-doped
γ-Fe_2O_3

CrO_2



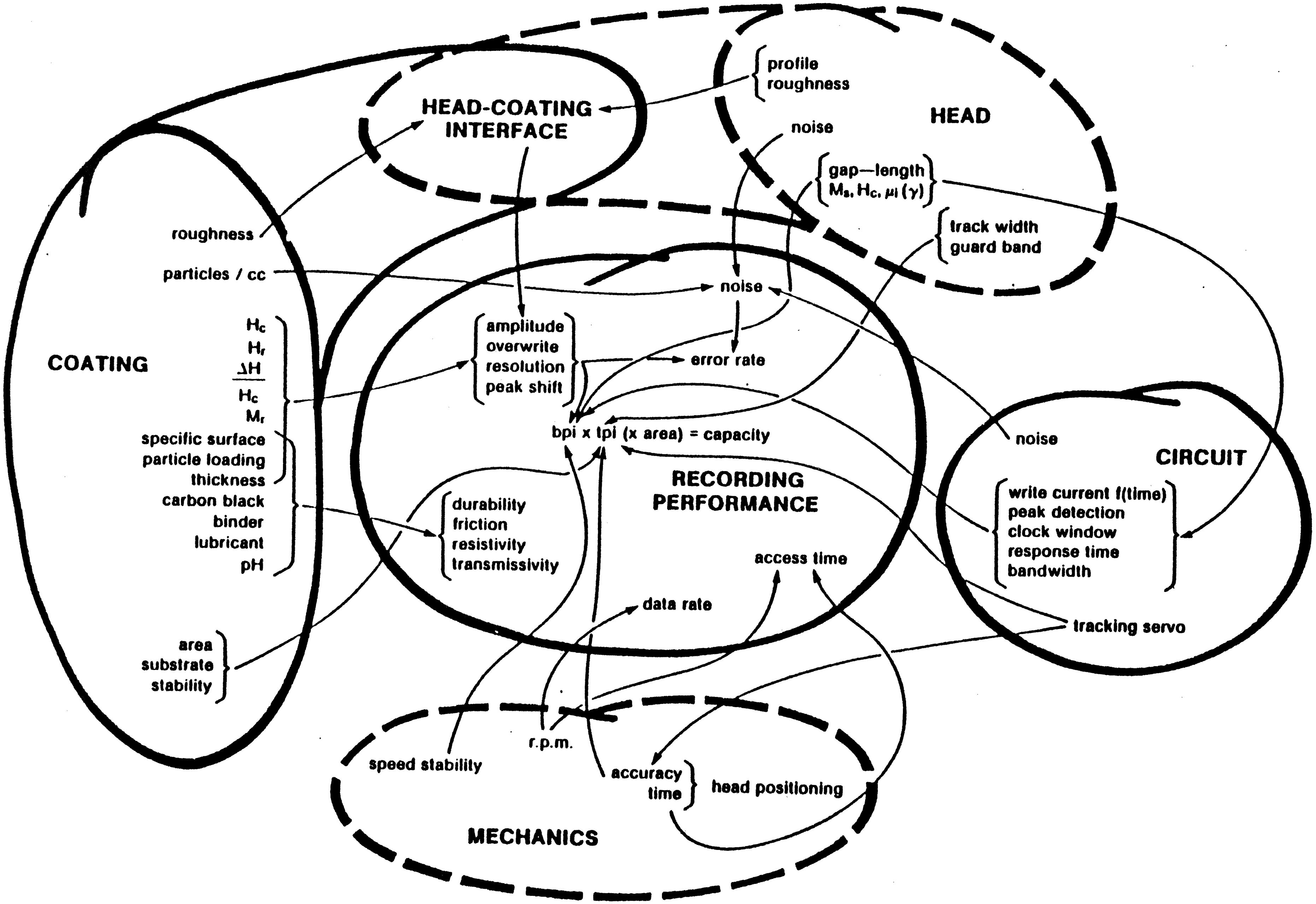
Oseroff, Clark, Schultz, Shtrikman
I.E.E.E. Trans. Mag. 1985

Particulate Media

- wide variety of magnetic properties
- magnetic properties from particles
- mechanical properties from binder
- high coating speeds ($\leq$ 130m/min)
- wide rolls ($\leq$ 1.3m)
- uniform, reproducible properties
- yields high → low cost

Thin Film Media

- thin coatings ($< 0.25\mu m$)
- magnetic properties not diluted by binder
- magnetic properties varied by changing deposition conditions.
- easier to coat on metallic than polymer substrates.


HEAD-COATING INTERFACE
HEAD
profile
roughness
noise
gap—length
M_s, H_c, μ_i (γ)
track width
guard band
COATING
roughness
particles / cc
H_c
H_r
$\frac{\Delta H}{H_c}$
M_r
specific surface
particle loading
thickness
carbon black
binder
lubricant
pH
area
substrate
stability
noise
amplitude
overwrite
resolution
peak shift
error rate
bpi x tpi (x area) = capacity
RECORDING PERFORMANCE
durability
friction
resistivity
transmissivity
access time
data rate
noise
CIRCUIT
write current f(time)
peak detection
clock window
response time
bandwidth
tracking servo
speed stability
r.p.m.
accuracy
time
head positioning
MECHANICS

G GATE