How material selection and processing affect the final magnetic properties

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APEC Phoenix 2021

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JC and his Bs&T...

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- experimental physicist & process engineer
- make and design ferrite 3Cx and 3Fx

FERROXCUBE
A YAGEO COMPANY

- sales amorphous metals 2605/2714/2705

Metglas®

- marketing nanocrystalline VP500F components

VAC
VACUUMSCHMELZE

- Bs & T Frankfurt am Main GmbH

Bs&T Analyzer

content

Bs & T Analyzer I

Sinus Magnetization AC

high excitation

IEC 62044-3

low excitation

IEC 62044-2

loss, μ_a driven by B mode

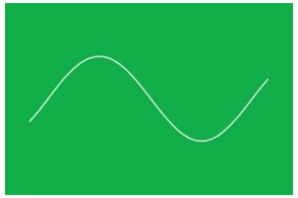
B_{peak}, loop driven by H mode

DC superposition

BsT-Pro

loss map (f, B, T, H_{DC}) μ_{rev} (f, B, T, H_{DC})

major, and biased minor loop



Pulse Magnetization

fast transit of magnetic state

dB/dt

IEC 60367-1 Annex G (393 IEEE)

BsT-Pulse

differential and **amplitude L**,

energetic L, power loss i.e. Q factor

Bs & T Analyzer II

Pulse Magnetization

fast transit of magnetic state

dB/dt

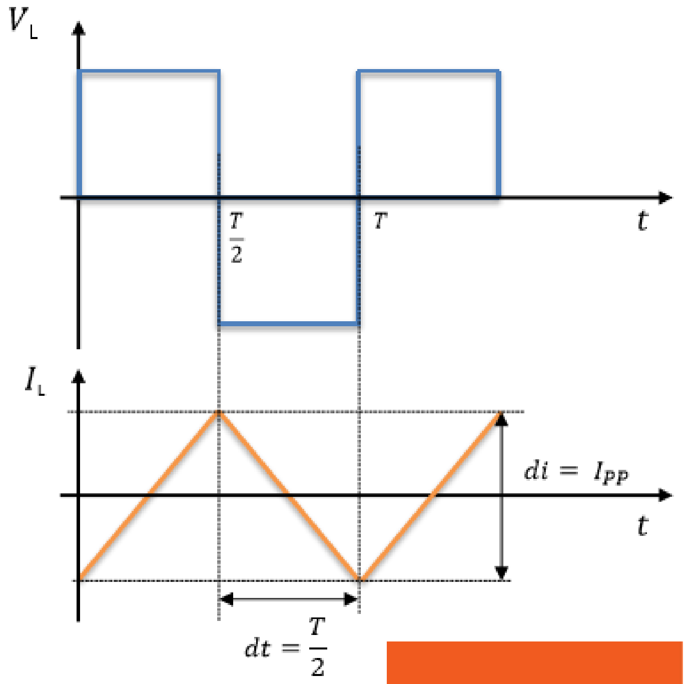
Damped oscillation

BsT-Pulse

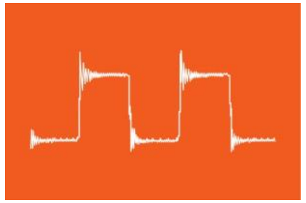
differential and amplitude L

energetic L, power loss

Square Wave



bipolar pulse magnetization



Critical review of ferrite material development of last decades

- 1995 – 2005
  classic way: loss density@100°C reduction due to improvement of iron oxide purity
  FXC: 3C8x ->3C9x, 3C91/90/93
  TSC: TSF 8040,7070,5099
  TDK: PC30->PC40, 46/45/44->47
  engineering crystalline anisotropy to ensure ***thermal*** design convergence @ 100°C T.C.<0

- 2005 – 2015
  temperature dependence of loss density is „disappeared“ T.C.=0
  95er phenomen: ALLFLAT, PC95/N95/3C95
  engineering to have two zero K_1 *vs.* T with Co^{2+} on the octahedral site

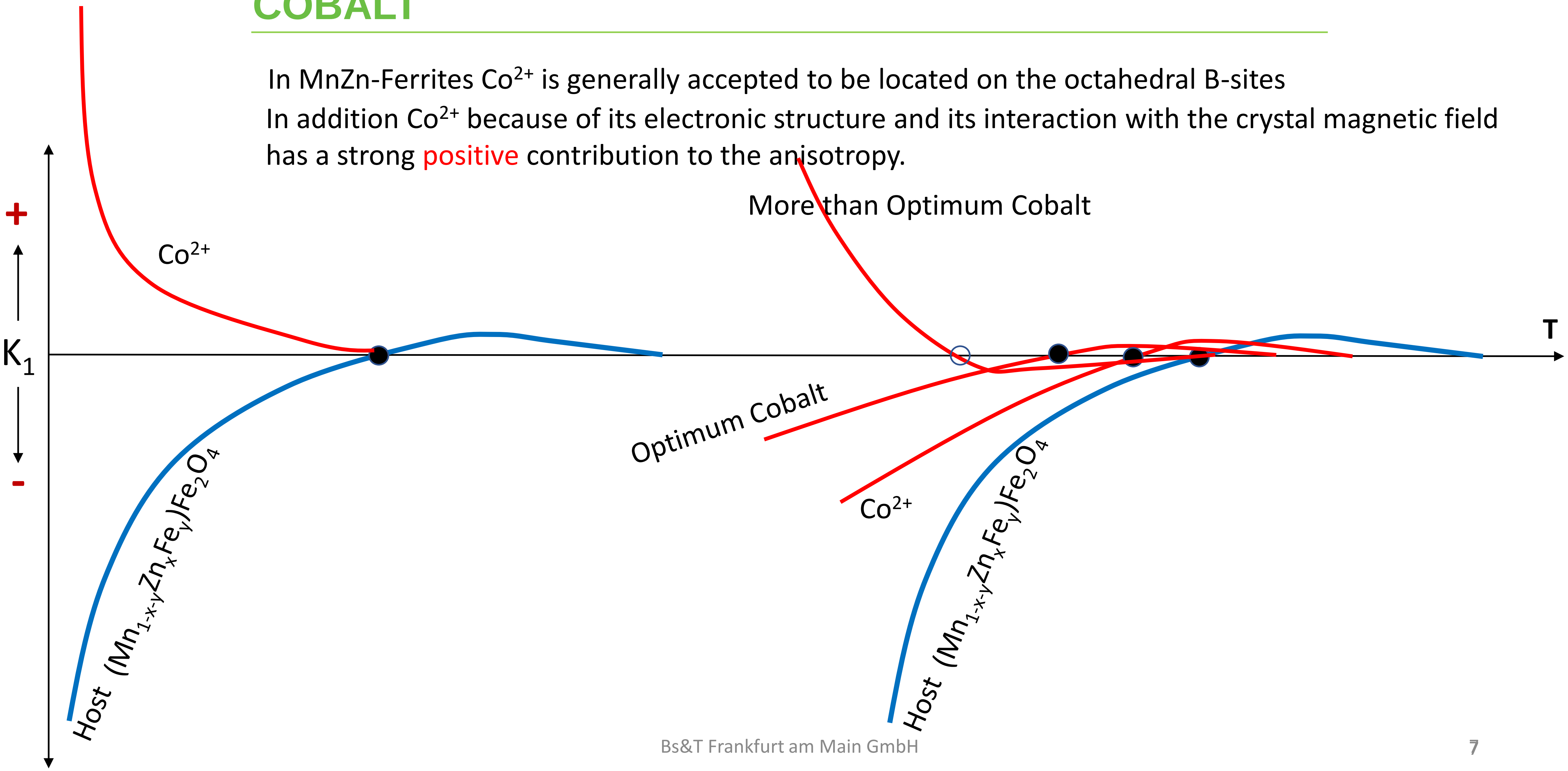
- 2015 – dito
  diversification of ***95er*** material A/F, W/H... and
  Positive temperature coefficient for mateiral over MHz PC200/210/220 T.C.>0

T.C. temperature coefficient* under large excitation

95er effect: MAGNETOCRYSTALLINE ANISOTROPY-COBALT

In MnZn-Ferrites Co^{2+} is generally accepted to be located on the octahedral B-sites

In addition Co^{2+} because of its electronic structure and its interaction with the crystal magnetic field has a strong positive contribution to the anisotropy.



H.F. Material competition landscape

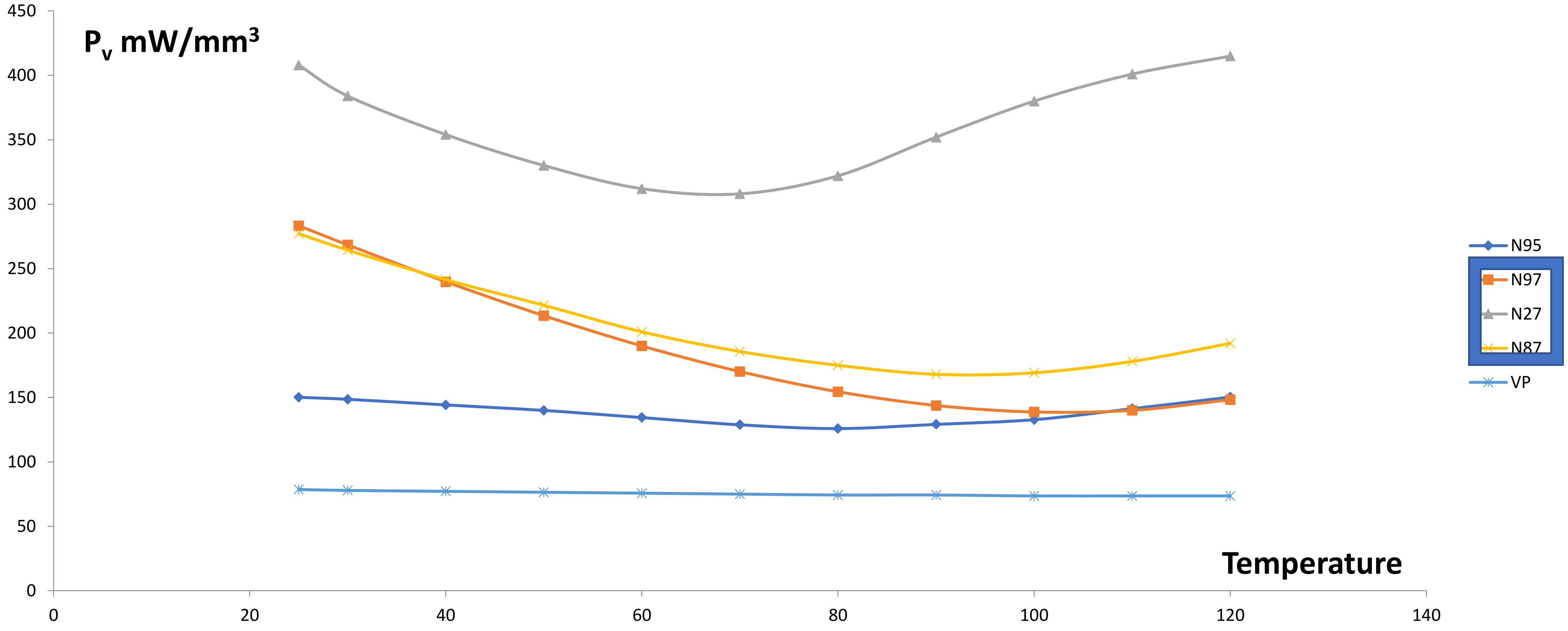
- Pronounced magnetocrystalline anisotropy (loss level overall due to high purity Fe_2O_3)
  3C80->3C90->3C94->3C97
  PC30->PC40->PC44->PC47
  N 27->N 67->N 87->N 97
- Dopants and microstructure
  ferrite is artificial ceramic, a semiconductor (new kids on the block) A. Goldman 90')
  powdering processing (chemical and mechanical nature);
  compacting and sintering (powder metalllurgical nature);
  (air)gapping, lapping (surface engineering nature);
  potting and conditioning of terminals, assemblying (mechanical engineering nature)
  clearly, application is *just* another postprocessing of ferrite making
- Competition: ferromagnetic material from alloy -> with higher B_s and higher T_c

  *nanocrystalline tape wound core to substitute toroidal ferrite **
  *metal alloyed powdered shaped core to challenge gapped ferrite design, mostly from thermal point of view ***

* Further reading: damp oscillation of nanocrystalline tape woud core for common mode choke

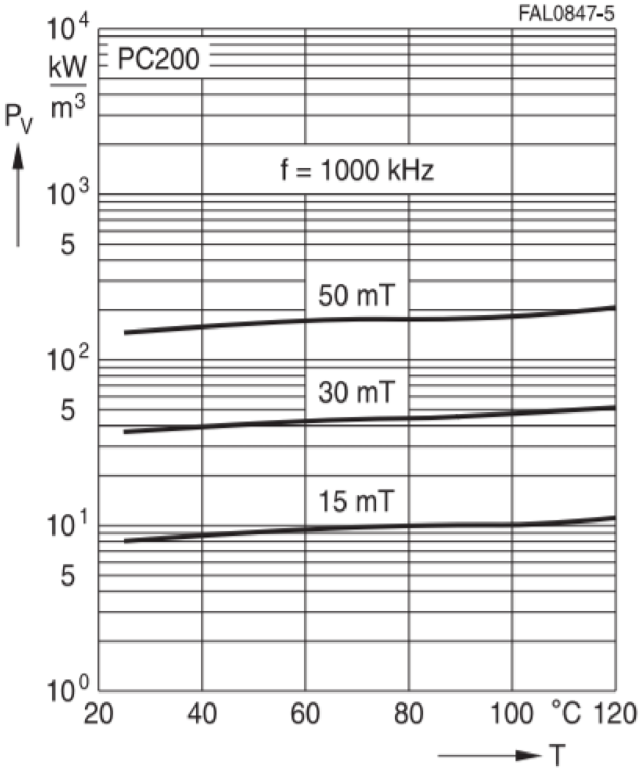
** Further reading: damp oscillation of metal alloyed powdered core

Loss volume density vs. Temperature comparison @ 100 kHz 200 mT

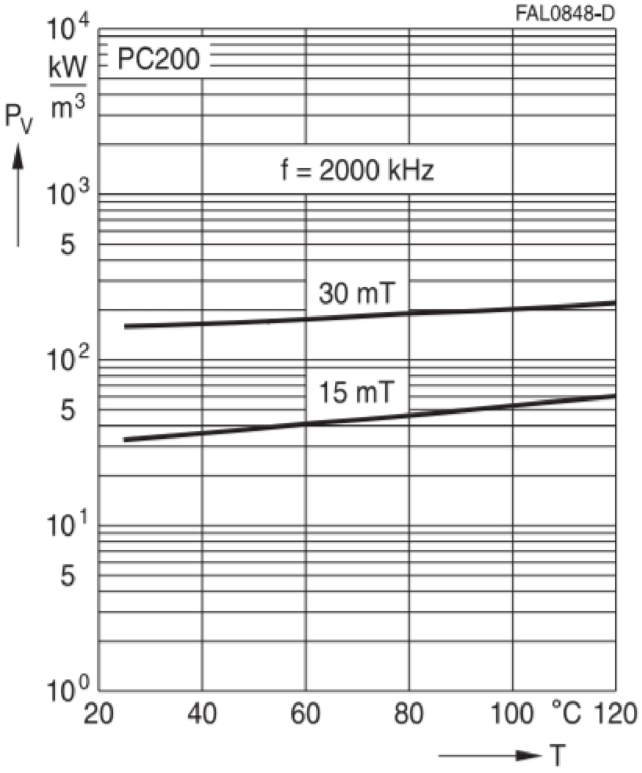


Loss volume density vs. T behavior in MHz range, size matters !

Relative core losses
versus temperature
(measured on R20 toroids, f = 1000 kHz)



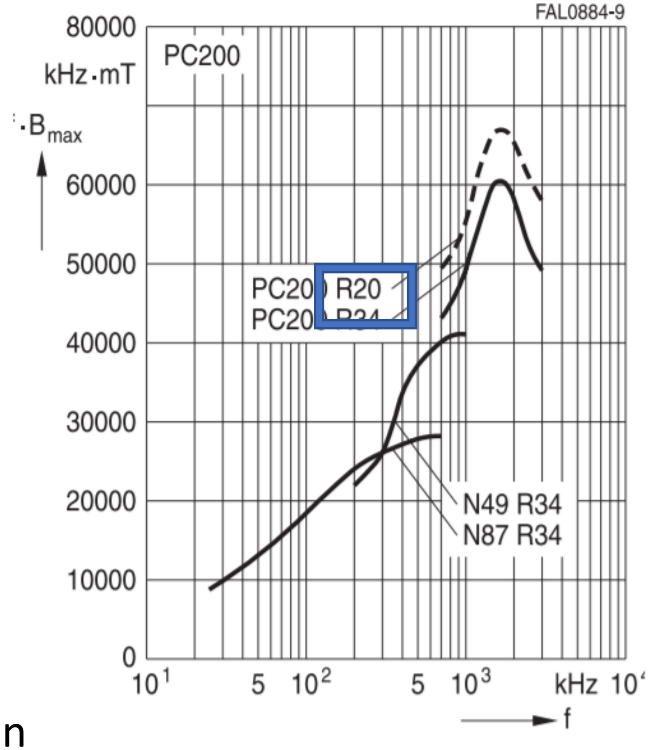
Relative core losses
versus temperature
(measured on R20 toroids, f = 2000 kHz)



SIFERRIT materials

PC200 (N59)

Performance factor
measured frequency
(T = 100 °C, P_V = 300 kW/m^3)



The ferrite loss increasing with high operation temperature, like copper

The core size, not only the material, is important for high frequency application

Design relevant parameters of inductive component

- Transformer design
  for high frequency efficient energy conversion, the only uncertainty is loss !
  simple treatement with Steinmetz coefficient (only 3 parameters), otherwise at least further 3 parameters needed to describe the loss vs. temperature dependence
  95er phenomen pleased circuit designer
  research of loss is unfortunately reduced to „renaissance“ of *Steinmetz* with data puzzle
- Choke design
  a dc biased high frequency ripple design can always to be approached with gapped ferrite core, the thermal management is of experimental nature, the thermal resistance* is simplified to describe typical behavior
  The current validation of magnetic components, only for PCB components standard IEC 62024 Ed.2 for rated current < 22 A

- Discrepency between typical and limit value increases

* Further reading: Hanna Curve reloaded with BsT-pulse

Further processing 1 Disaccomodation

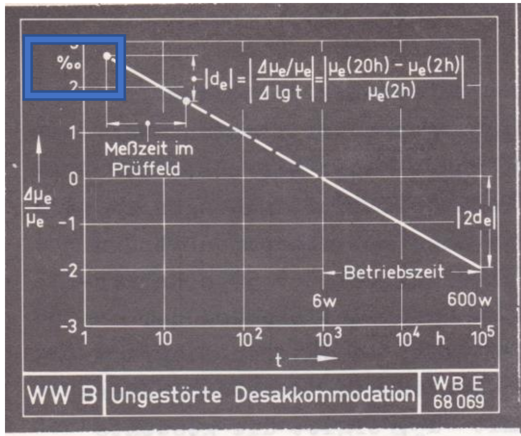


Bild 1

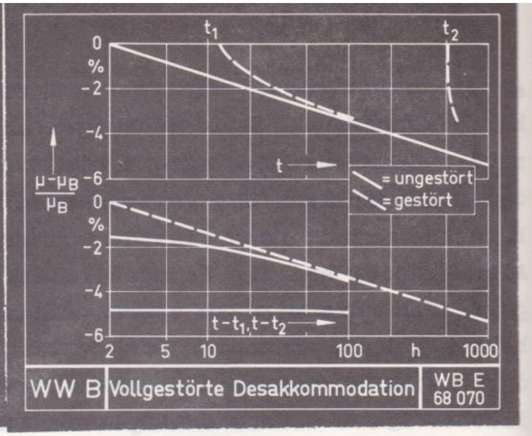


Bild 2

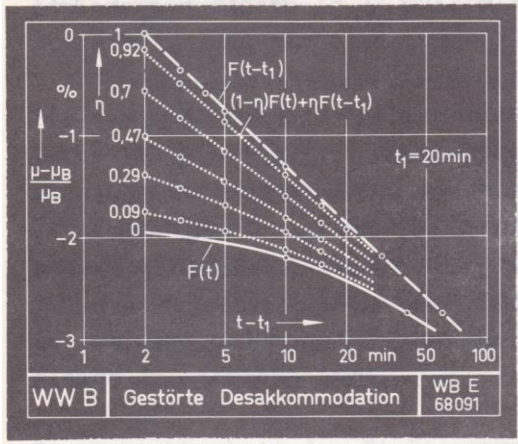


Bild 3

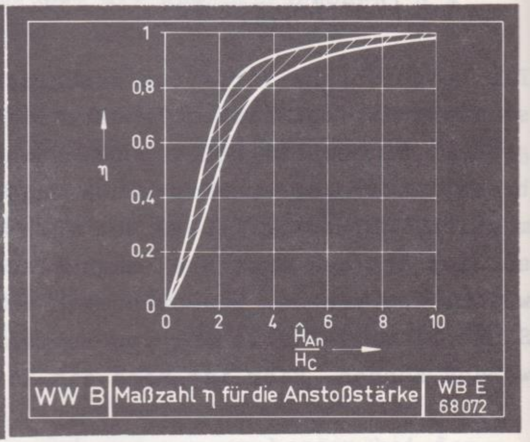


Bild 4

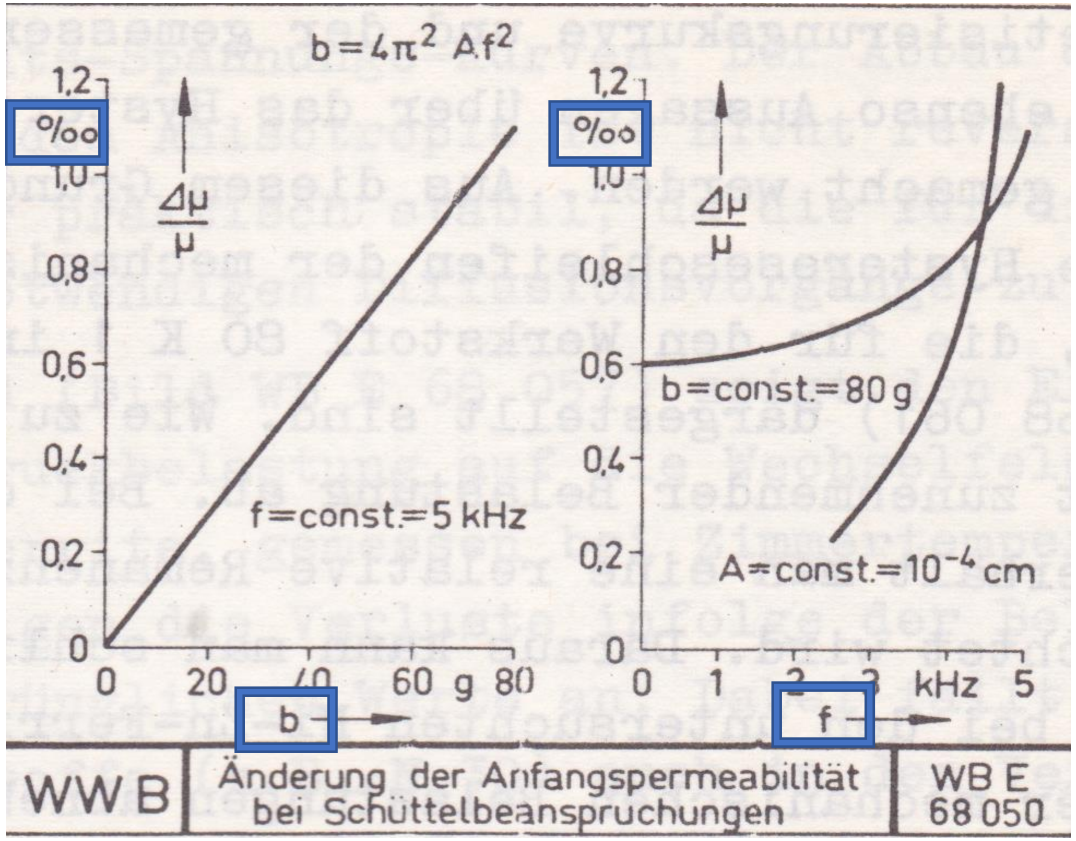
Picture 1: undisturbed disaccomodation $\frac{\Delta\mu_e}{\mu_e} = d_e lg \frac{t_E}{t_A}$

Picutre 2: complete disturbed discaccomodation with reference μ_B
(2 h after full impetus)

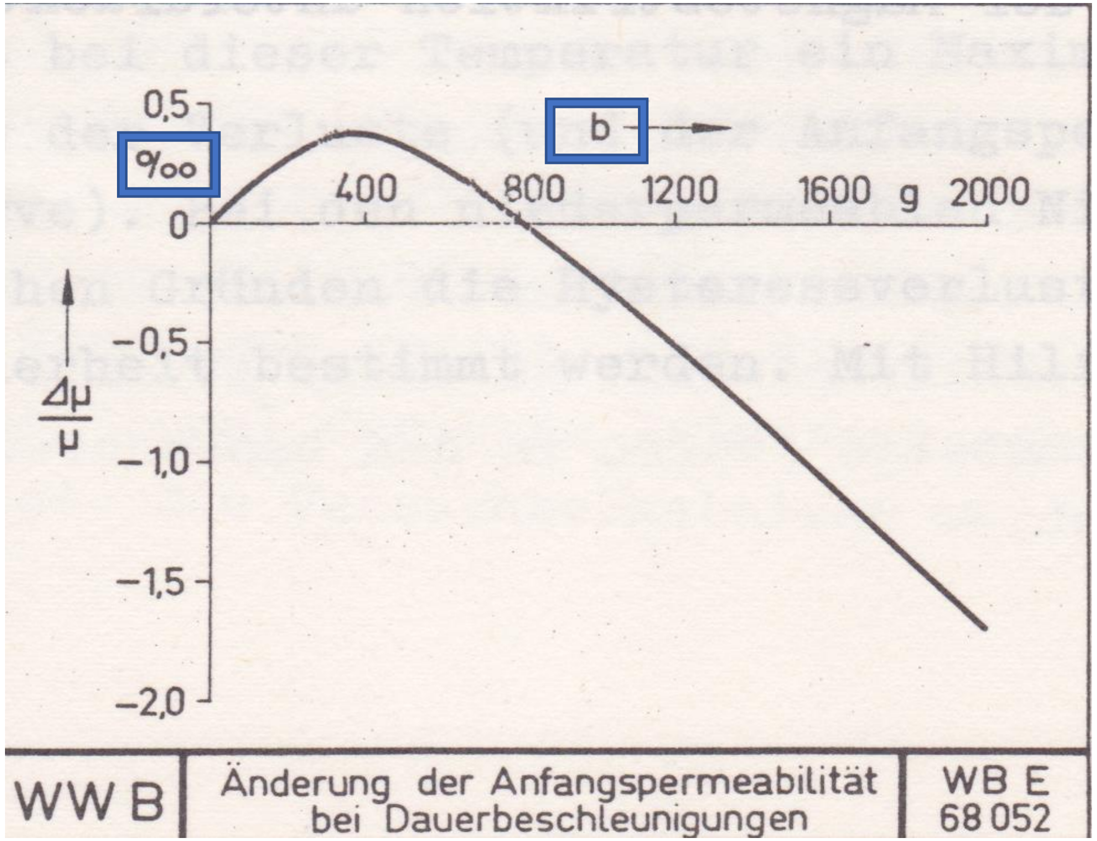
Picture 3: disturbed disaccomodation with reference μ_B
(2 min each partial impetus), ***η*** as impetus ratio
Picture 4: relationship ***η*** vs. ratio of H_{AC}/H_c H_{AC} as impulsed fieldstrength, and H_c as coecivity, ***η*** can be generalized as thermodynamic and mechanical impetus

G. Roespel 1968

Further processing 2 dynamic load



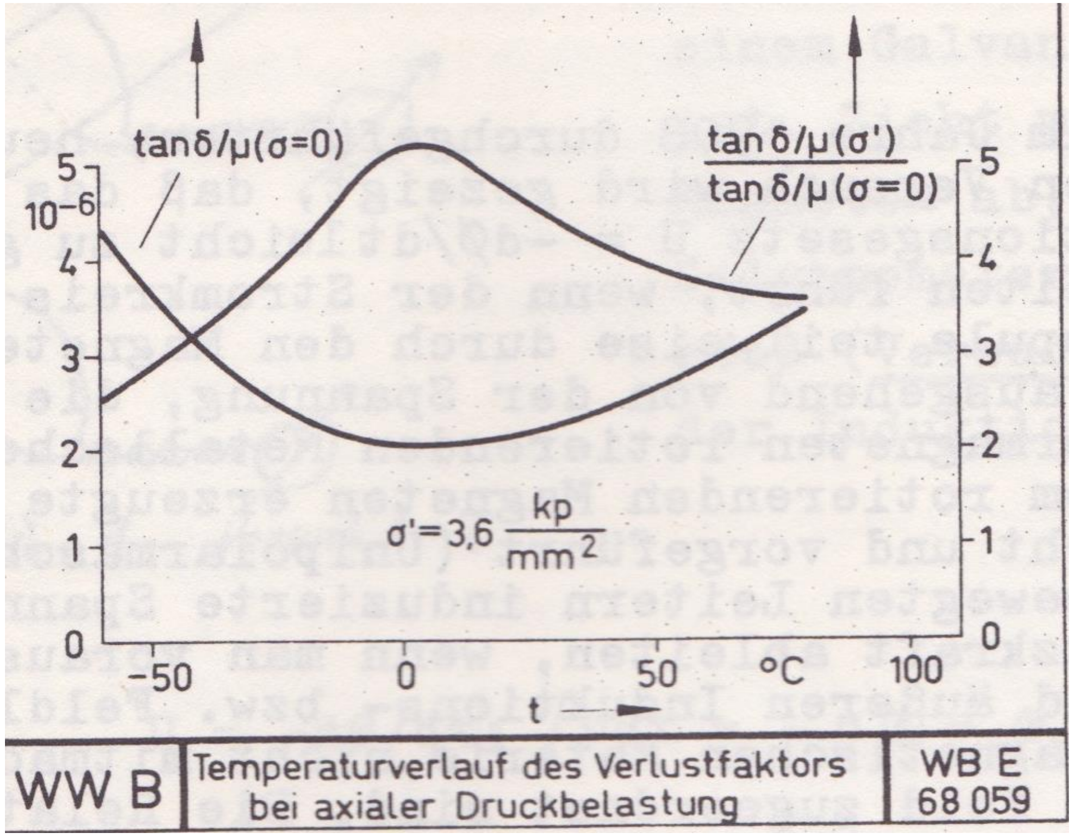
Permeability deviation vs. amplitude b and frequency f of shaking stress



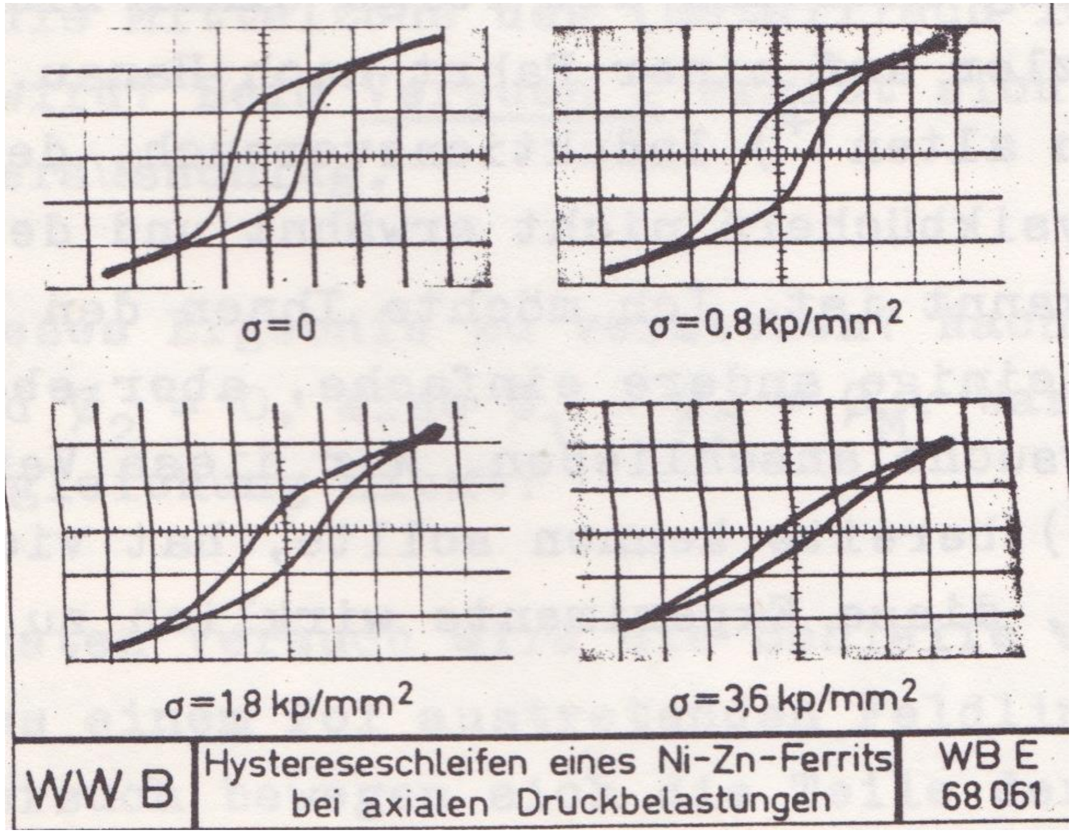
Permeability deviation vs. lateral acceleration in centrifuge

D. Linke 1968

Further processing 3 static axial load



Loss factor vs. temperature under axial pressure



Hysterese loop of *perminvar* NiZnFerrite under different axial pressure

D. Linke 1968

Energy expression and its magnitude (soft magnetics)

Energy terms	Coefficient	Definition	Range
Exchange energy	A (J/m)	Material constant	$10^{-12} – 2 \cdot 10^{-11}$ J/m
Anisotropy energies	K_u, K_c...(J/m^3)	Material constant	± (10^{-1} – 10^{4}) J/m^3
External field energy	H_{ex} J_s (J/m^3)	***H_{ex} = external field*** J_s = saturation magnetization	Open, depending on ***field*** magnitude
Stray field energy	K_d (J/m^3)	$K_d = J_s^2/2\,\mu$	$0 – 3 \cdot 10^6$ J/m^3
External stress energy	$\sigma_{ex}\,\lambda$ (J/m^3)	***σ_{ex} = external stress*** $\lambda =$ magnetostriction constant	Open, depending on ***stress*** magnitude
Magnetostrictive self energy	$C\lambda^2$ (J/m^3)	C = shear modulus	$0 – 10^3$ J/m^3

It is impossible to assign a single origin for domain structures in all kinds of materials.
The non-local energy terms, stray field energy, are responsbile for the development of domains, i.e. loss

The thermodynamically stabile domain treatment of uniform, reversible magnetiaztion is material characterisation
The considerable different magnitude of anisotropies in shape and size delivers more argument for core characterisation

Major technological bottleneck: validation technique

- Loss mechanism still not understood, no analytic micromagnetic model (defects, disclosure etc.), loss measurement, like domain analysis, is indispensible
  material loss – core loss – power loss – energy loss

- Standard confusion & ignorance
  TC68 alloy vs. TC51 ferrite

  the major difference in loss measurement of alloy and ferrite, is the systemic influence of temperature dependence.

  material / core / component

material characteristic:	closed magnetic circuit
core characteristic:	open magnetic circuit

Summary

- Vertical integration of ferrite making as business consequence
  TDK, material – core – component – system.....

- Much easier to communicate about good & bad results, rather than about magnetics (material TC68/core IEEE393/coil IEEE389)
- The existing IEC standards helpful to understand ferrite, IEC62044-2 for small signal and IEC62044-3 for large signal
- Soft ferrite is right in midlife-crisis,
  - 80 years after discovery,
  - meticulous research in magnetism in 40-50s (Snoek, Néel)
  - extensive material research in 70-80s (International Conference Ferrite)
  - experienced flourish business with SMPS (MOSFET) in 90-00s
  - facing now challgenge by other new kids (rapid quenched alloys) 10-20s
    - can be helped with better understanding by application engineers for WBG applications