Ferrite Cores
The Rest of the Story

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Source material credit

- Most figures taken from Fair-Rite catalogs (13th and 14th editions)
- Very similar material available from competing vendors

Background

- Ferrite properties often misunderstood or insufficiently understood by designers
- Results are often costly redesigns and program delays

Common applications

- Transformers (primarily in higher frequency switching mode power supplies) and inductors
  - Typically many turns on various core shapes

- Frequency dependent “resistors” (losses) (primarily in EMC control)
  - Typically few turns using sleeve or toroid

Ferrite core review

- Ferrite has many formulations having different properties for example:
  - Manganese (Mn) – e.g. grade 85 used primarily for transformers with μ_i of 900
  - Manganese zinc (MnZn) – e.g. grade 73 used for transformers, inductors and EMC suppression at low frequencies with μ_i of 2500
  - Nickel zinc (NiZn) – e.g. grade 43 used primarily for EMC suppression at medium and higher frequencies with μ_i of 850
  - Nickel zinc (NiZn)– e.g. grade 61 used primarily for EMC suppression at higher frequencies with μ_i of 125

Availability

- Huge variety of shapes and sizes available
    - E and I
    - Toroids
    - Cup cores
    - Rods
    - Sleeves
    - Beads
    - etc
    - Custom

Ferrite properties

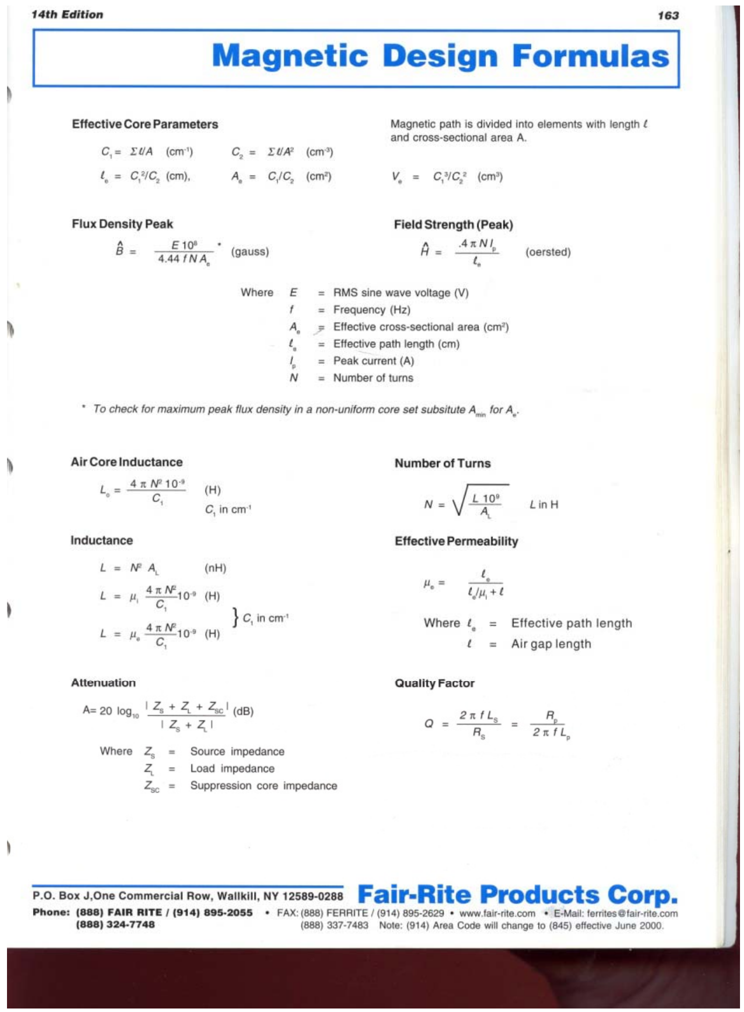
- Initial permeability – from about 20 to over 10,000
- Some highly conductive (MnZi) (50 Ω cm)
- Some highly resistive (NiZn) (1x 10^7 Ω cm)
- Curie temperature from 120 to > 500 °c
- Some have dimensional resonance frequencies (MnZi) and may crack or shatter if excited at these frequencies

Many factors involved in optimal designs

- Inductance and coupling (permeability)
- Losses (core and winding)
- Saturation (loss of most of inductance)
- Capacitance effects on bandwidth
- Temperature rise
  - Curie temperature (loss of inductive properties)
  - Physical damage
- Dimensional resonance (core cracking)
- Size, weight and cost (application driven issues)
- Others (tolerances, skin effect and proximity effect)

Application notes too brief

Formulas typically presented do not consider many key parameters



14th Edition 163

Magnetic Design Formulas

Effective Core Parameters

Magnetic path is divided into elements with length ℓ and cross-sectional area A.

$C_1 = \Sigma \ell/A$ (cm^{-1}) $\quad C_2 = \Sigma \ell/A^2$ (cm^{-3})

$\ell_e = C_1^2/C_2$ (cm), $\quad A_e = C_1/C_2$ (cm^2) $\quad V_e = C_1^3/C_2^2$ (cm^3)

Flux Density Peak

$$\hat{B} = \frac{E\,10^8}{4.44\,f\,N\,A_e}{}^{*} \text{ (gauss)}$$

Field Strength (Peak)

$$\hat{H} = \frac{.4\,\pi\,N\,I_p}{\ell_e} \text{ (oersted)}$$

Where
E = RMS sine wave voltage (V)
f = Frequency (Hz)
A_e = Effective cross-sectional area (cm^2)
ℓ_e = Effective path length (cm)
I_p = Peak current (A)
N = Number of turns

* *To check for maximum peak flux density in a non-uniform core set subsitute A_{min} for A_e.*

Air Core Inductance

$$L_o = \frac{4\,\pi\,N^2\,10^{-9}}{C_1} \text{ (H)}$$

C_1 in cm^{-1}

Number of Turns

$$N = \sqrt{\frac{L\,10^9}{A_L}} \quad L \text{ in H}$$

Inductance

$L = N^2\,A_L$ (nH)

$$L = \mu_i \frac{4\,\pi\,N^2}{C_1} 10^{-9} \text{ (H)}$$

$$L = \mu_e \frac{4\,\pi\,N^2}{C_1} 10^{-9} \text{ (H)}$$

C_1 in cm^{-1}

Effective Permeability

$$\mu_e = \frac{\ell_e}{\ell_e/\mu_i + \ell}$$

Where ℓ_e = Effective path length
ℓ = Air gap length

Attenuation

$$A = 20 \log_{10} \frac{|Z_S + Z_L + Z_{SC}|}{|Z_S + Z_L|} \text{ (dB)}$$

Where Z_S = Source impedance
Z_L = Load impedance
Z_{SC} = Suppression core impedance

Quality Factor

$$Q = \frac{2\,\pi\,f\,L_s}{R_s} = \frac{R_p}{2\,\pi\,f\,L_p}$$

P.O. Box J, One Commercial Row, Wallkill, NY 12589-0288 **Fair-Rite Products Corp.**
Phone: (888) FAIR RITE / (914) 895-2055 (888) 324-7748 • FAX: (888) FERRITE / (914) 895-2629 (888) 337-7483 • www.fair-rite.com • E-Mail: ferrites@fair-rite.com Note: (914) Area Code will change to (845) effective June 2000.

Designer must address additional factors

Issues for this presentation

Serious design problems often result from ignorance or neglect of several properties

- Complex permeability of ferrites
- Capacitance effects
- Temperature effects
- Potential core cracking at dimensional resonance frequencies
- Others (less common)

Not Really Hard to Understand
Can Cause Major Problems

Complex Permeability

Complex permeability

- Complex permeability of ferrites is a key to proper ferrite core application design
- Considering only the initial or effective permeability can result in serious problems

Key formula

$$\overline{\mu} = \overline{\mu_s'} + j\overline{\mu_s''}$$

Permeability is a complex parameter

Formula components

$$\overline{\mu} = \overline{\mu_s}' + \overline{j\mu_s}''$$

Real part relates to inductive properties **and is highly frequency dependent**

Imaginary part relates to loss properties **and is highly frequency dependent**

Components of loss (μ″)

- Several component properties are typically included in μ″
  - Hysteresis
  - Eddy Currents
  - Residual losses
  - Others and Unknowns

Good news!

- μ_s' and μ_s'' are measurable and often provided
- Measurement requires RF instrumentation

Frequency dependence of μ_s' and μ_s'' for Fair-Rite Grade 73

Constant initial permeability

Ferrimagnetic resonance at 500 kHz

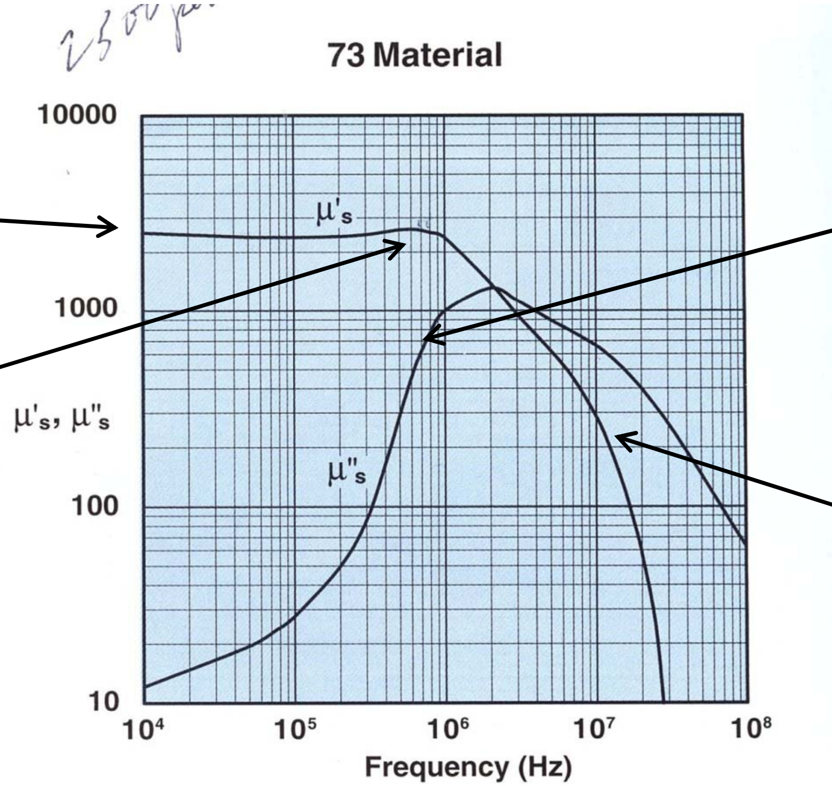


Figure 6 Complex Permeability vs. Frequency Measured on a 2673000301 bead using the HP 4284A and the HP 4291A.

Rapid rise in losses

Rapid loss of permeability

Frequency dependence of μ_s' and μ_s'' for Fair-Rite Grade 43

Ferrimagnetic resonance at 2 MHz

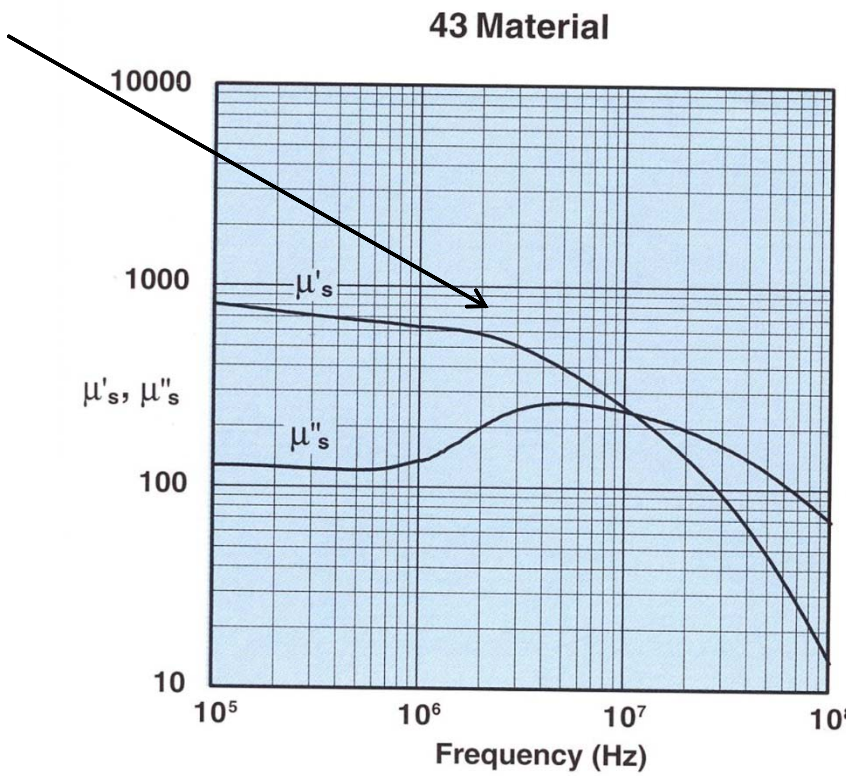


Figure 8 Complex Permeability vs. Frequency Measured on a 17/10/6mm toroid using the HP 4284A and the HP 4291A.

Frequency dependence of μ_s' and μ_s'' for Fair-Rite Grade 61

Ferrimagnetic resonance at 20 MHz

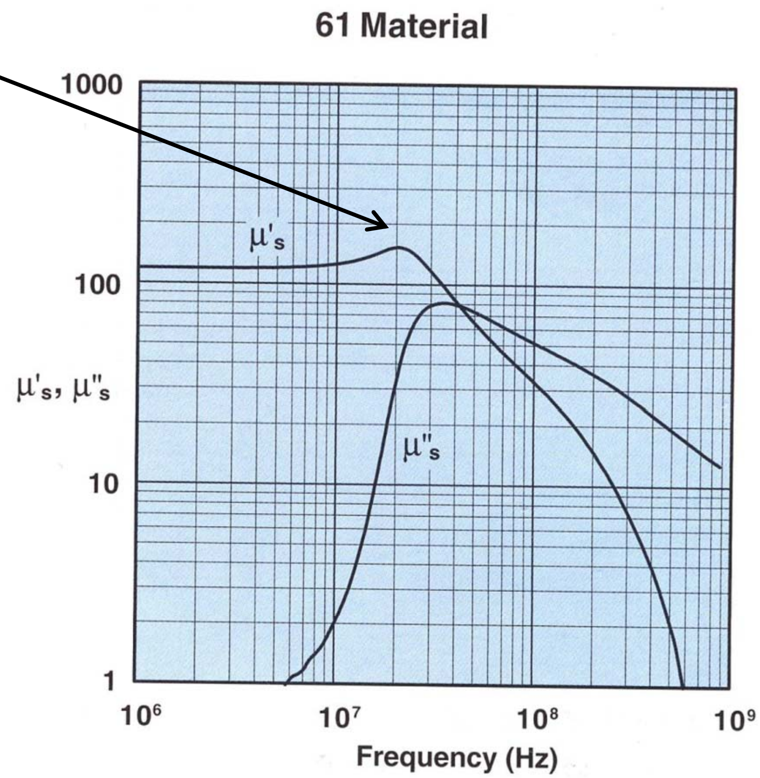


Figure 10 Complex Permeability vs. Frequency Measured on a 17/10/6mm toroid using the HP 4284A and the HP 4291A.

What does this show?

Good transformer design region – low losses and high real component of permeability

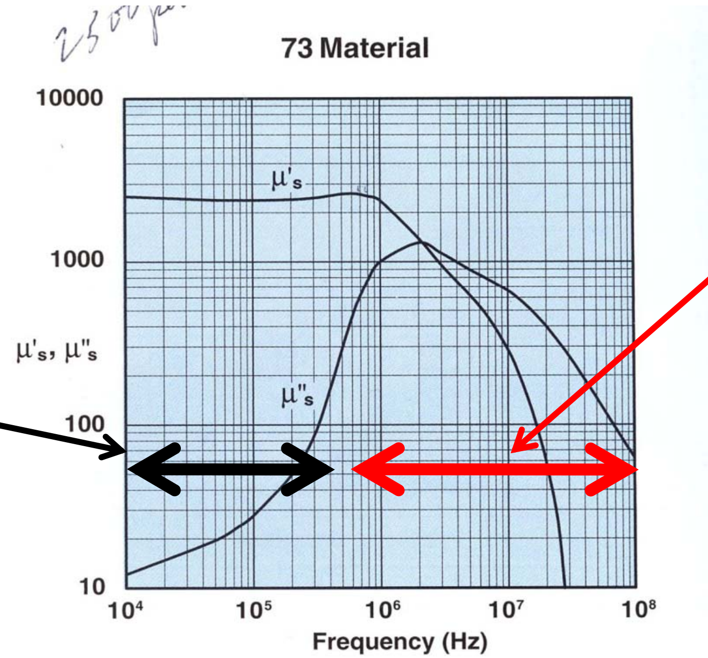


Figure 6 Complex Permeability vs. Frequency Measured on a 2673000301 bead using the HP 4284A and the HP 4291A.

Good variable resistance (loss) region for EMC

Two basic modes of application for ferrites

Looking further (series model)

For a given component:

$Z = j\omega L_s + R_s = j\omega L_o(\mu_s' + j\mu_s'')$ ohm

Where L_o = air core inductance

Then:

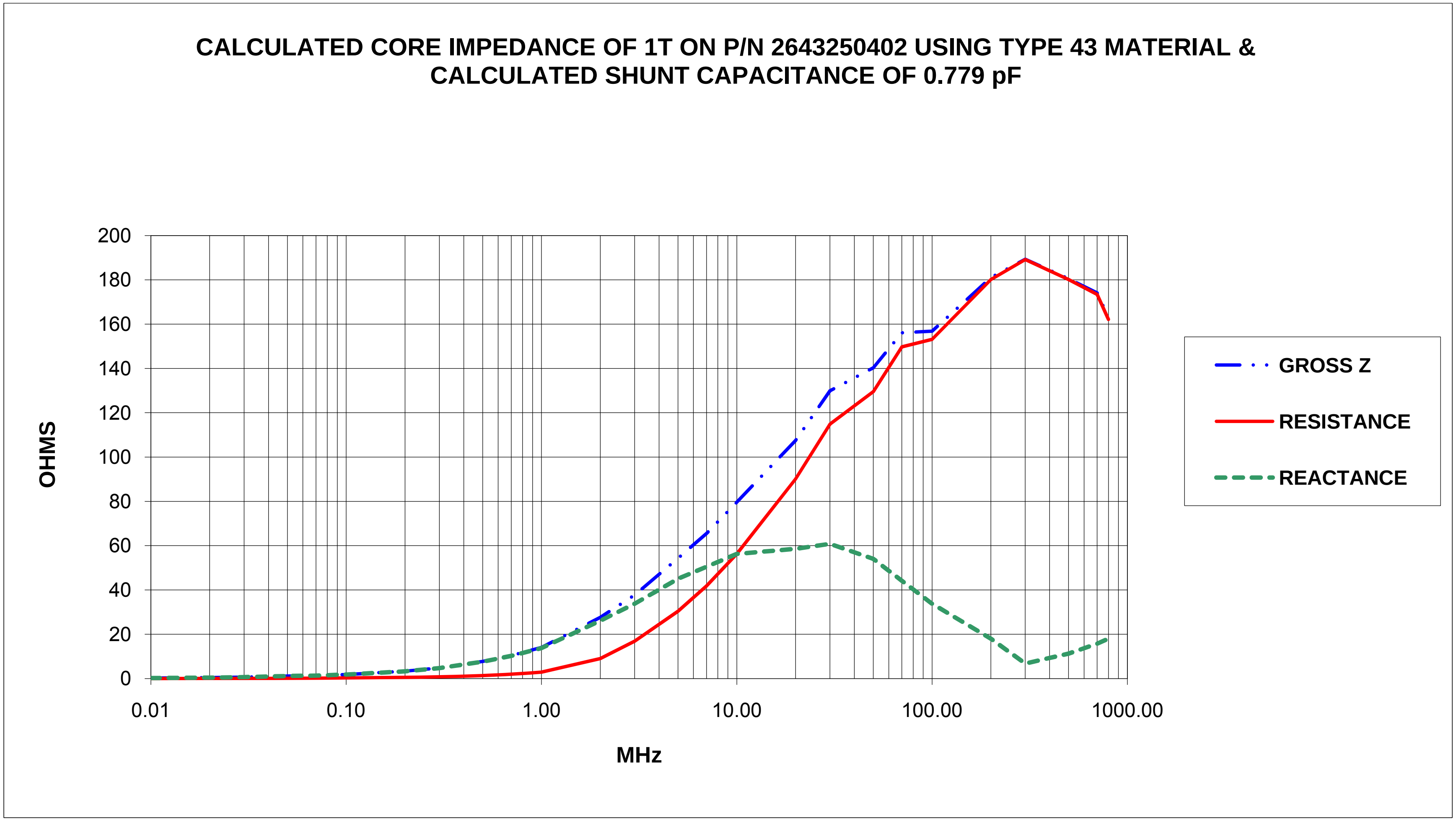
$\omega L_s = \omega L_o \mu_s'$ ohm (inductive reactance part)

$R_s = \omega L_o \mu_s''$ ohm (resistive – loss part)

Actual impedance values calculable

- Employ formulas from prior slide (and other references)
- Developing EXCEL© tool for this purpose

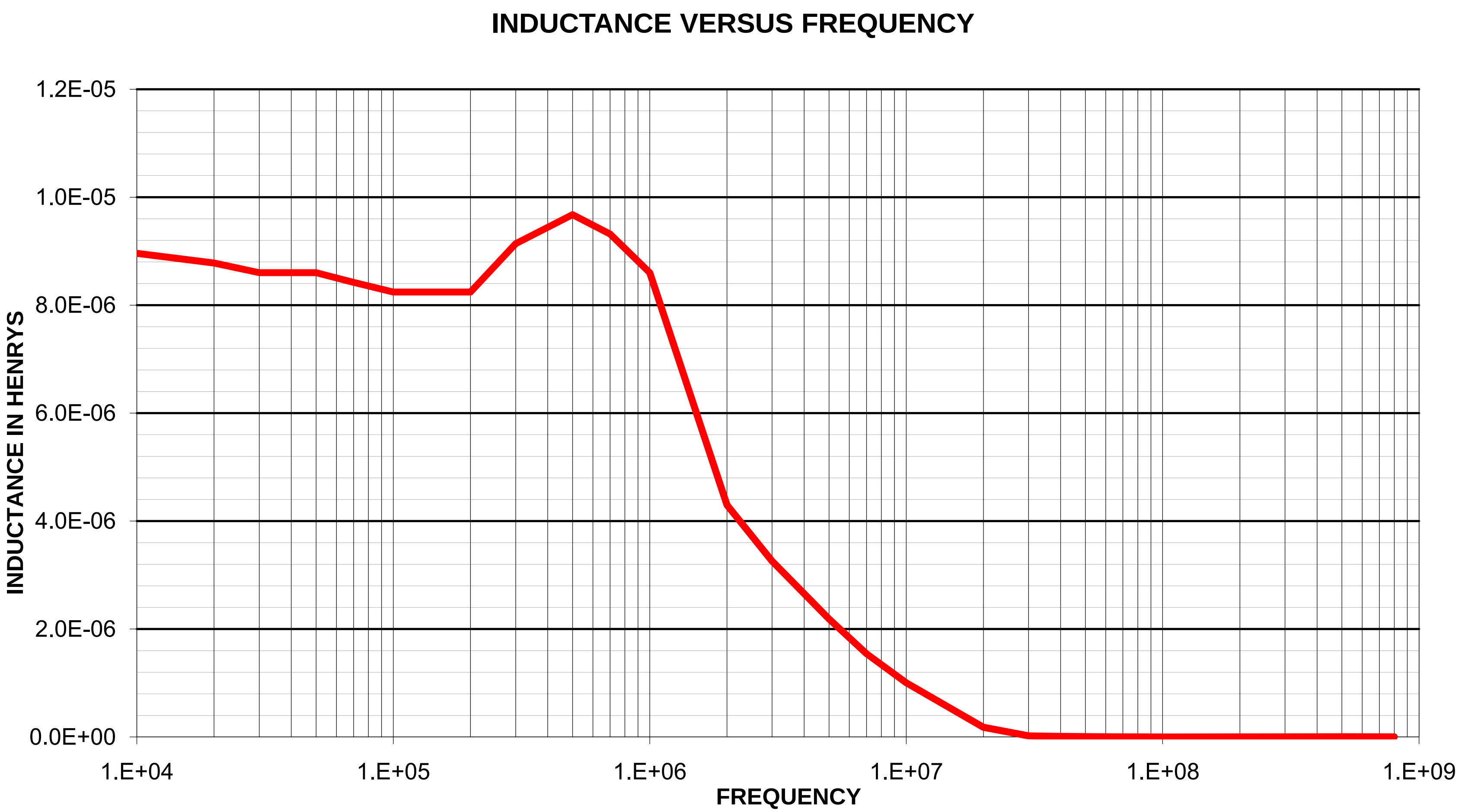
Sample computation output



Inductance concerns

- Inductance is frequency dependent especially near and above ferrimagnetic resonance
  - As shown μ_s' rises and drops rapidly
  - Therefore inductance <u>drops</u> rapidly
  - **Transformers and inductors may essentially cease to function as planned in this region**

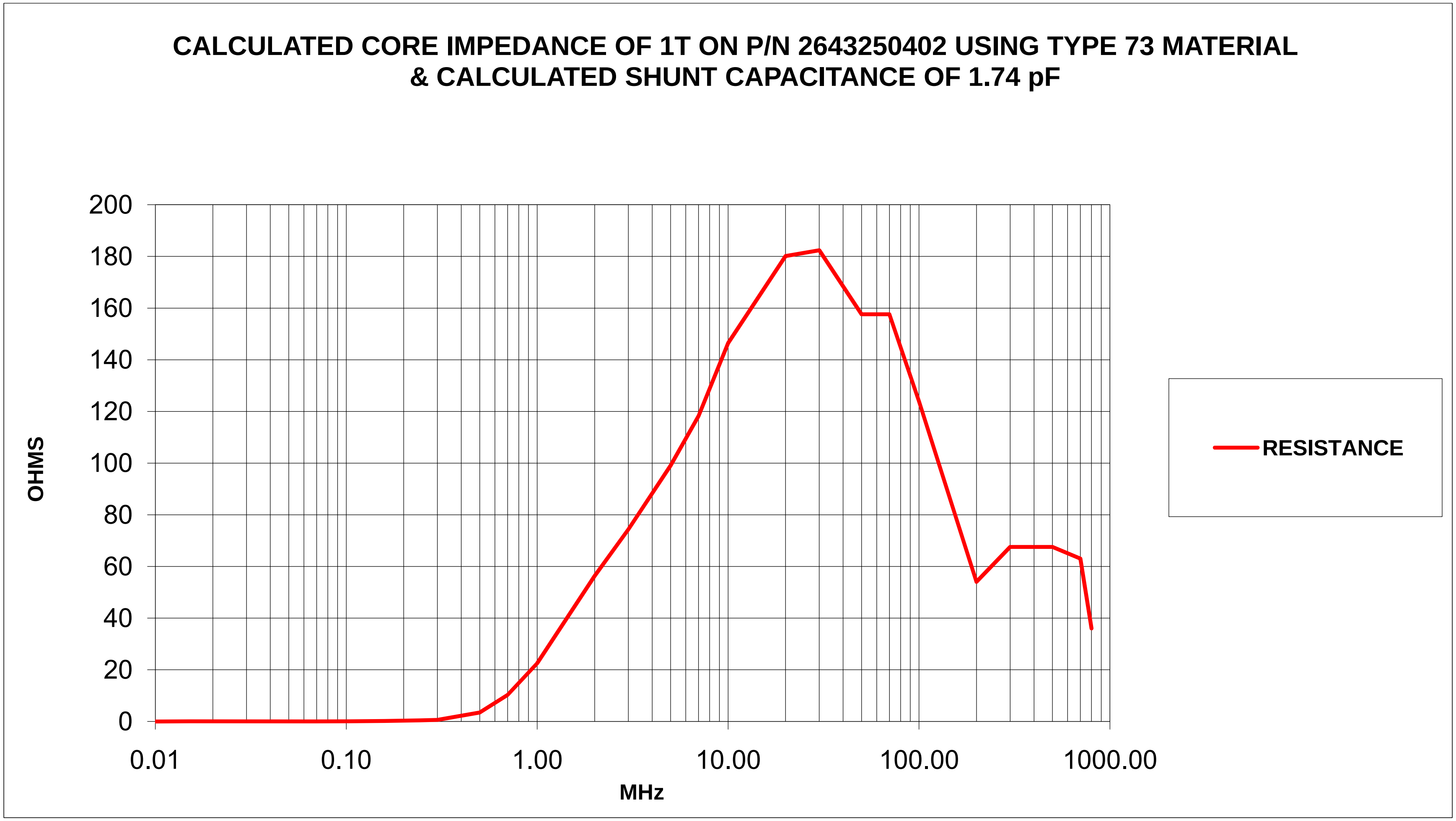
Example of Fair-Rite 73 grade inductance vs. frequency



"Resistance" (loss) concerns

- "Resistance" is also frequency dependent especially near and above ferrimagnetic resonance
  - As shown μ_s" rises dramatically
  - Therefore "resistance" <u>increases</u> rapidly
- **Components become frequency dependent "resistors"**
  - **Very useful in EMC applications**
  - **Dissipation of undesired signals is goal**
- Watch dissipation levels resulting from signals in this high loss frequency range

Example of "resistance" of Fair-Rite 73 grade



Winding capacitance effects often very significant
Information on calculation hard to find

Winding capacitance issues

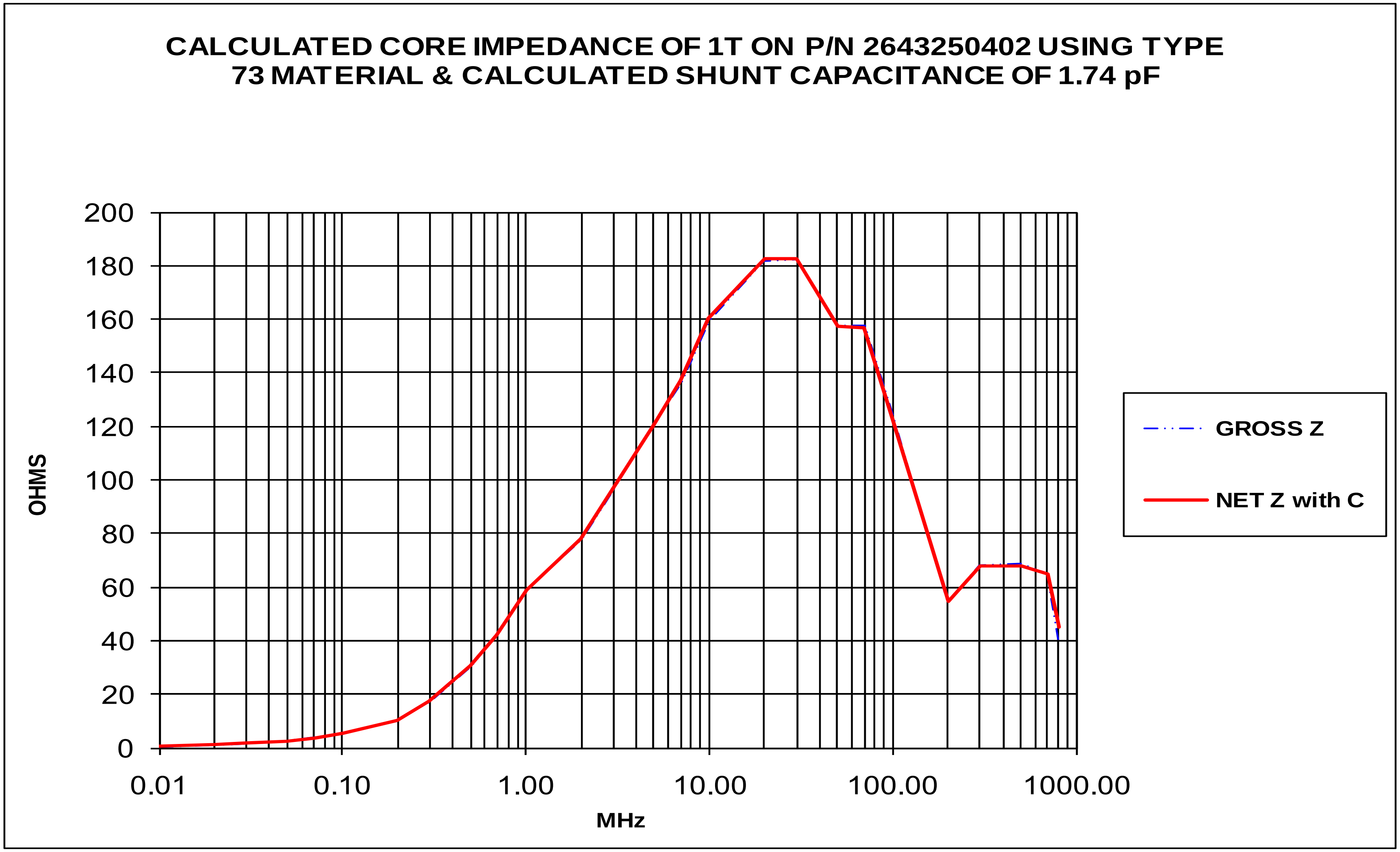
Winding capacitance issues

- Winding capacitance shunts desired inductance
  - Non-conductive ferrite adds minimal capacitance (but windings do have self capacitance to consider)
  - Conductive cores act like capacitor plates and significantly increase capacitance and its undesired effects
- Stray capacitance to surroundings may also be of concern (beyond our scope tonight)

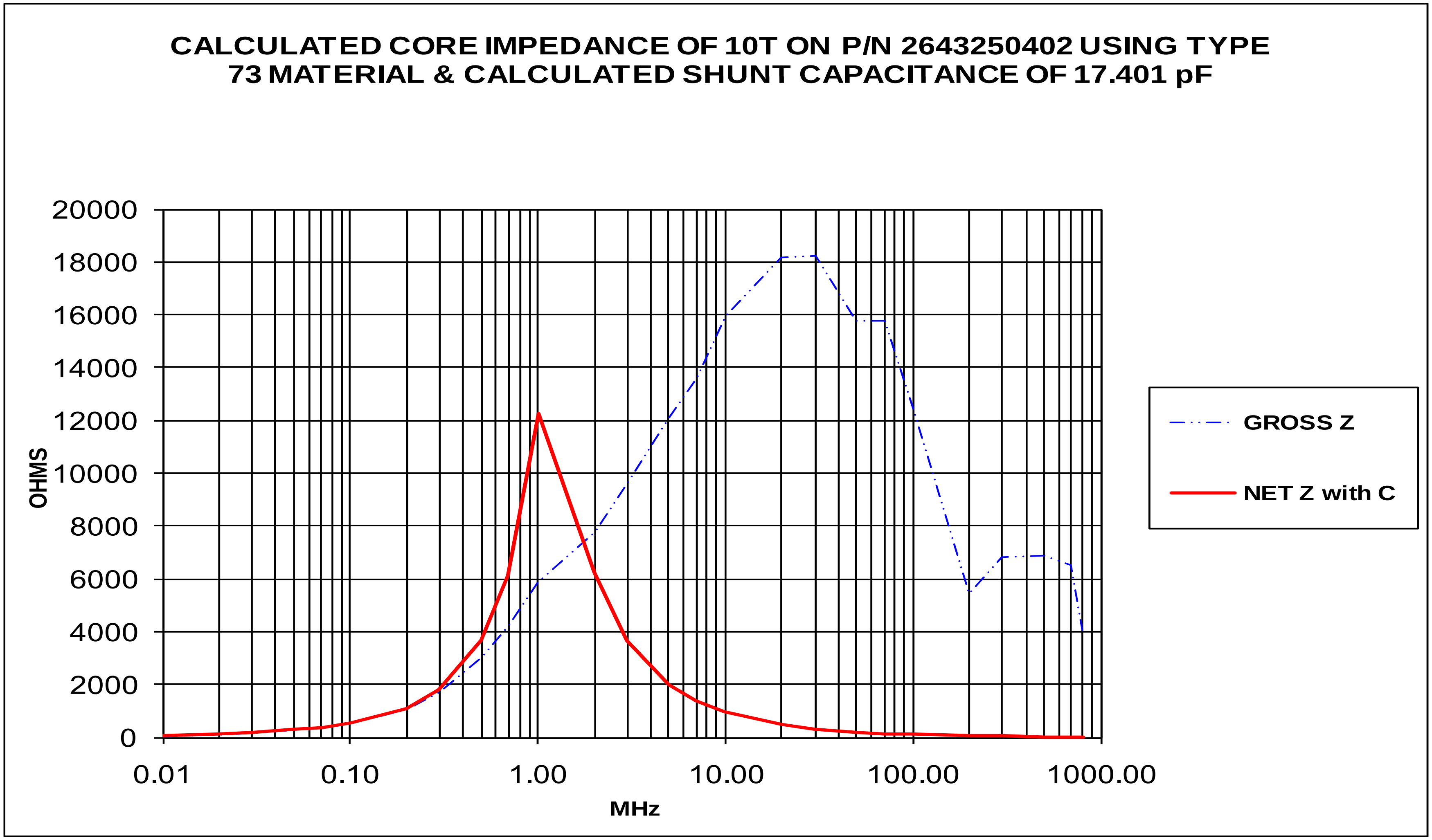
Modeling winding capacitance

- Models are elusive (out of scope for tonight)
  - Non-conductive model by Medhurst (1947) based upon empirical measurements of many air core inductors and quoted by Snelling in his book
  - Conductive core model (one) by Duerdoth (1946) and also quoted by Snelling in his book
- Newer models may exist

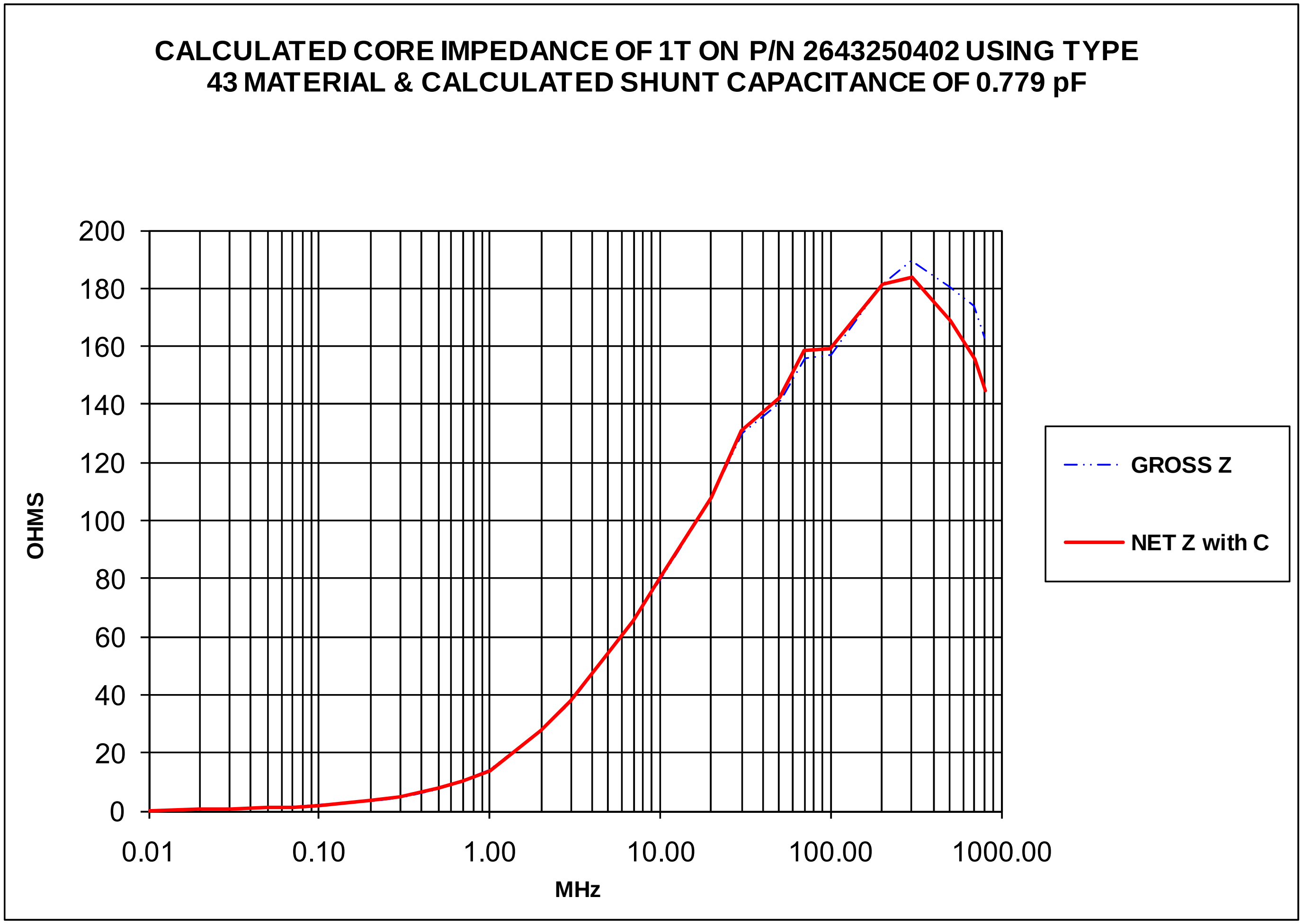
Example of conductive core with 1 turn



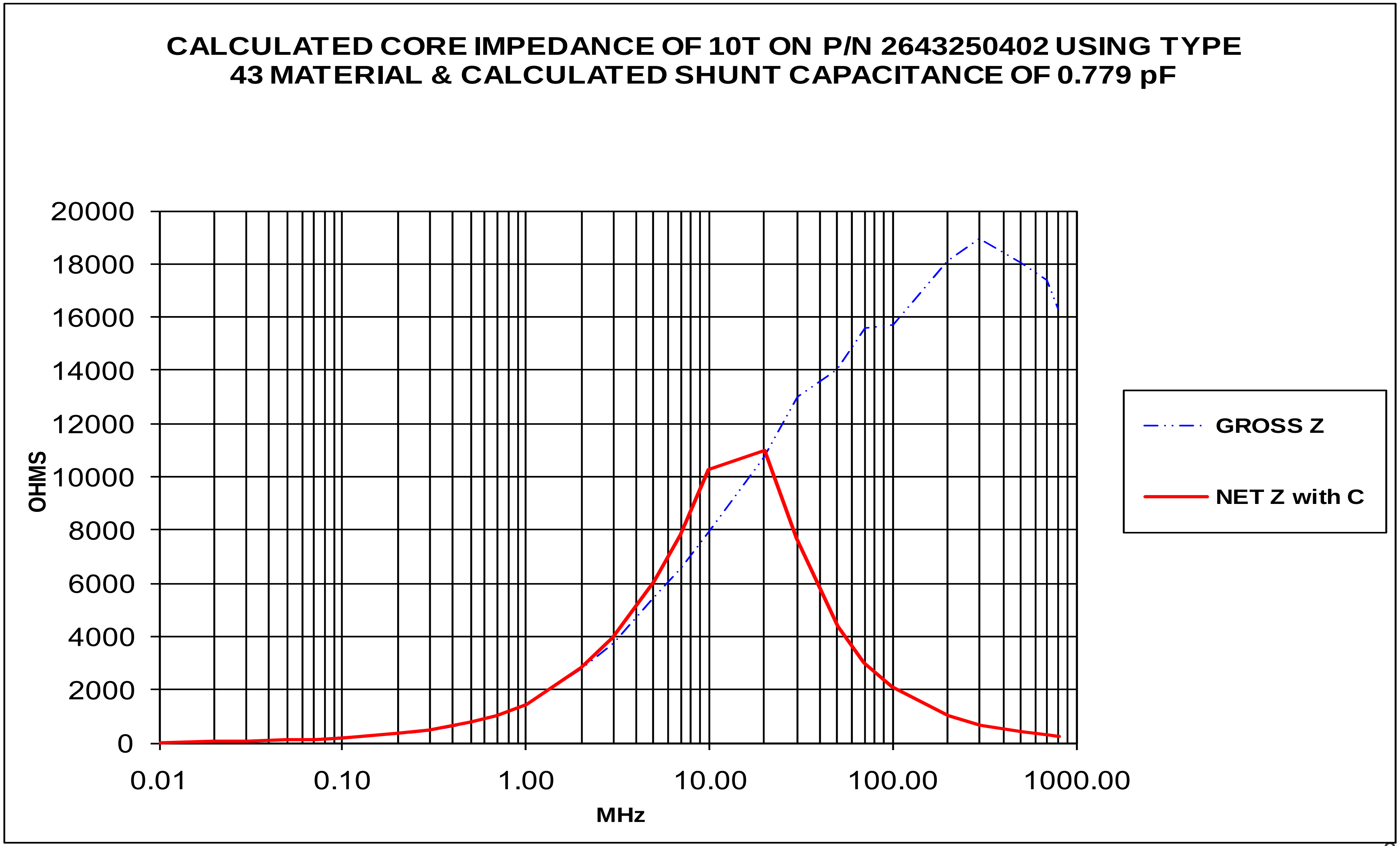
Example of conductive core with 10 turns



Example of non-conductive core with 1 turn



Example of non-conductive core with 10 turns



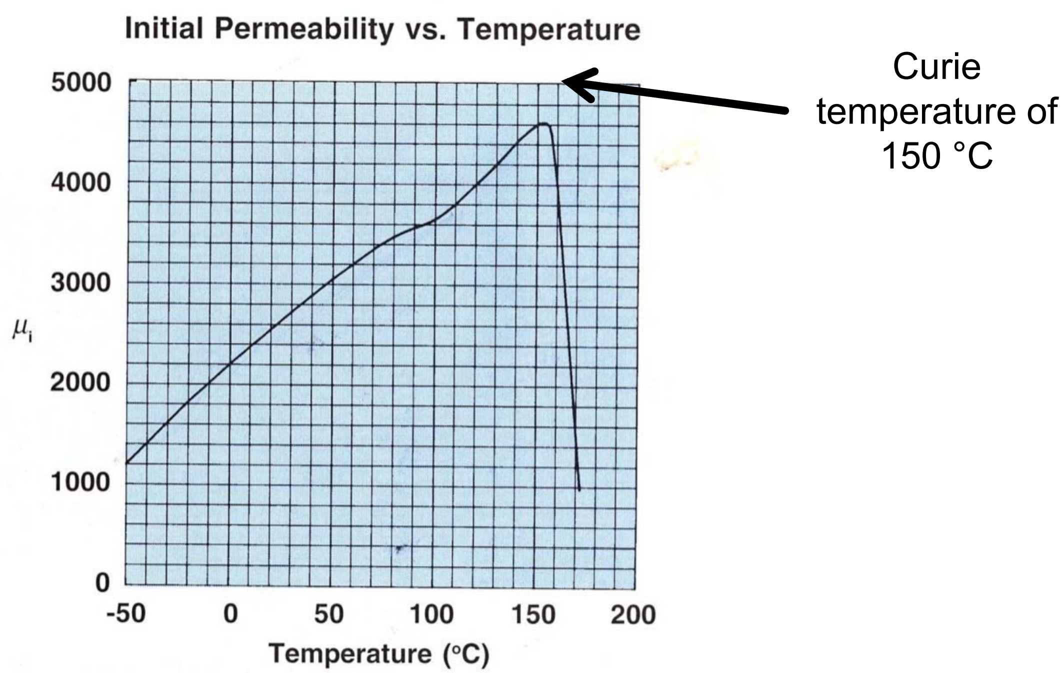
Be sure to investigate these issues

Temperature issues

Temperature issues

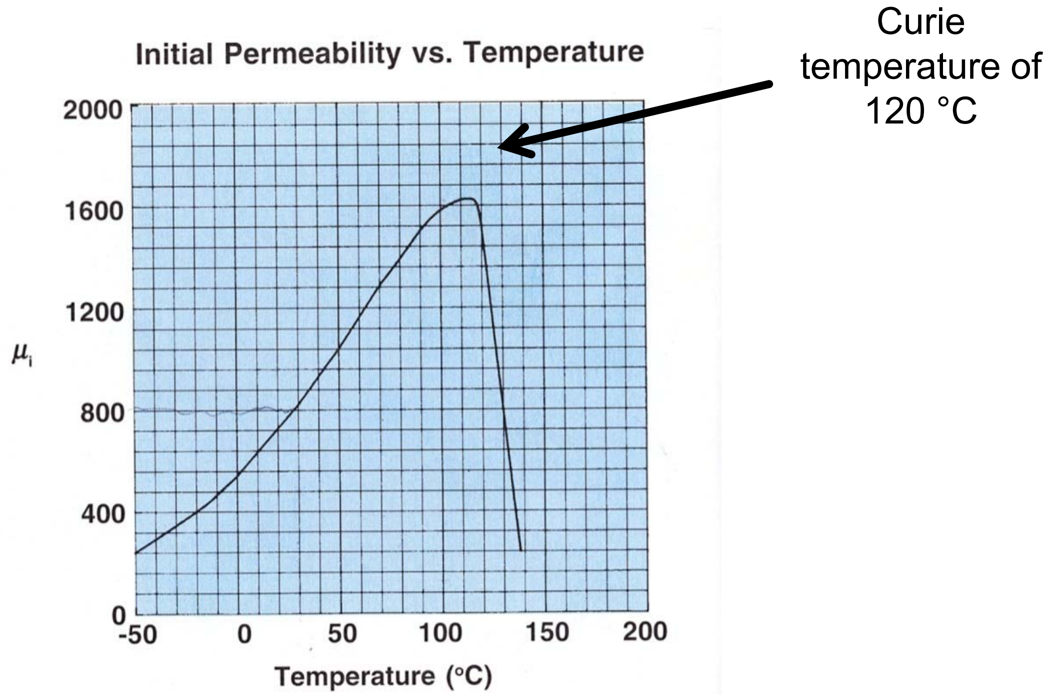
- Must carefully watch ferrite core temperature
  - Ambient levels
  - Rise due to core and wire losses
  - Dissipation of harmonic content in high loss range
- Temperature significantly effects permeability and impedance
- Curie temperature is definite limit for applications

Permeability of Grade 73 versus temperature



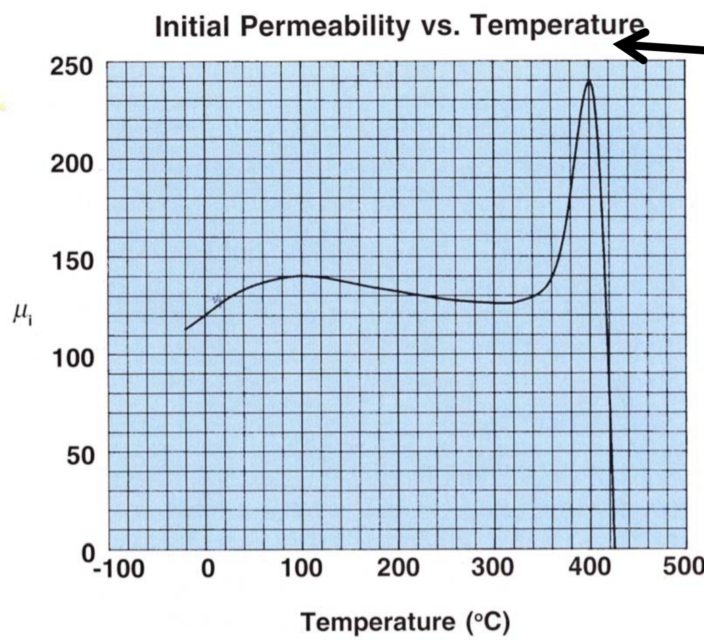
Measured on a **25.4mm** OD toroid at 100 kHz using a HP 4275A.

Permeability of Grade 43 versus temperature



Measured on a **25.4mm** OD toroid at 100 kHz using a HP 4275A.

Permeability of Grade 61 versus temperature



Measured on a **25.4mm** OD toroid at 100 kHz using a HP 4275A.

Curie temperature of 400 °C

Temperature effects on impedance

High temperatures lower Z dramatically

Material dependent property

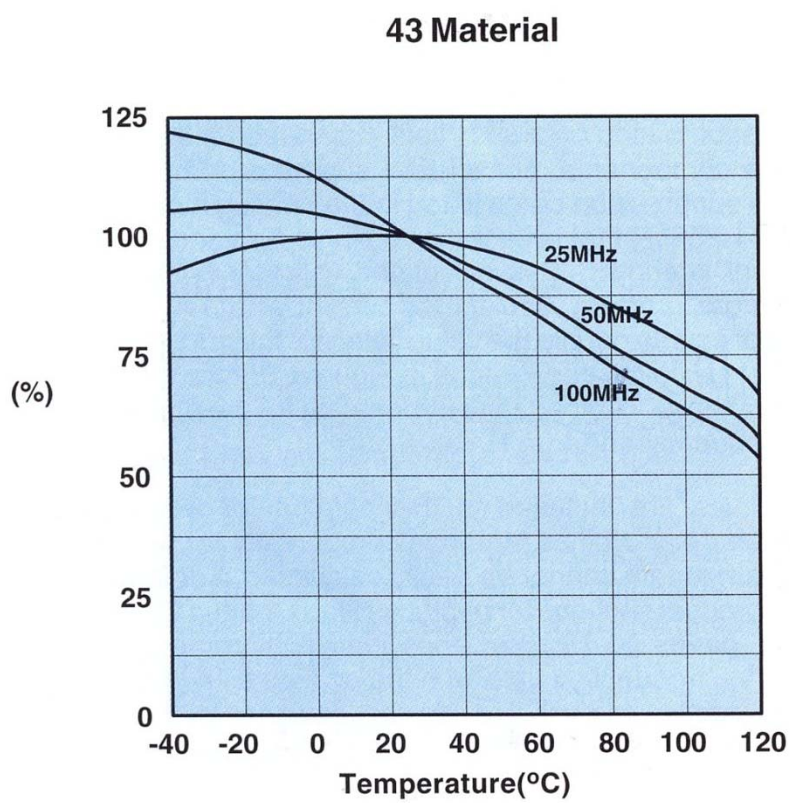


Figure 13 Percent of Original Impedance vs. Temperature Measured on a 2643000301 using the HP4291A.

Even though μ_i increases with temperature z goes down

Dealing with temperature issues

- Temperature will result in significant change in permeability and impedance
  - Very large changes are likely
  - Virtual total permeability loss is possible (Curie temperature exceeded)
  - Physical damage or destruction is possible
- Consider all factors and know where you are
  - Account for changes and tolerances (+/- 20%)

Dimensional resonance

Uncommon but serious problem

Dimensional resonance

- Dimensional resonant frequency is related to product of permeability and conductivity
- Simultaneously high conductivity and high permeability cores may experience resonances at quite low frequencies (kHz)
- Resonance may result in cracking or shattering of cores

Formula

- Generally only applies to MnZi cores of moderate size
- $F_{MR} = 5700/(\pi*((10*OD)+(10*ID)/2))$

Dealing with dimensional resonance

- Calculate frequencies for high permeability high conductivity cores (MnZi)
- Compare resonant frequencies to expected excitation frequencies
- Change core material or size if necessary to avoid problems

Summary

- Incorporate complex permeability issues into designs
  - Stay in high permeability low loss region for most transformers and inductors (considering relevant frequencies)
  - Select cores for maximum loss at undesired frequencies for EMC applications
- Watch maximum temperatures in application
- If using MnZi cores be alert to dimensional resonances

References

- *Fair-Rite Soft Ferrites*, 13th Edition, 1998, Fair-Rite Products Corporation, Wallkill, NY.
- *Fair-Rite Soft Ferrites*, 14th Edition, 2000, Fair-Rite Products Corporation, Wallkill, NY.
- ***Soft Ferrites, Properties and Applications*, 2nd Edition, 1988, Snelling, E. C., Butterworths, Stoneham, MA.**
- *Soft Ferrites 1998 Data Handbook MA01*, 1998, Phillips Electronics NV, The Netherlands.

Speak up

Questions