Measurement and Modeling of Core Loss in Powder Core Materials

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Trends for AC Power Loss of High Frequency Power Magnetics

APEC 2012

Outline

- Core Loss Measurement Technique
- Developing a Core Loss Model
- Fitting the Model to the Data
- Effect of Temperature on Core Loss
- Effect of Duty Cycle on Core Loss
- Effect of DC Bias on Core Loss

Powder Core Materials

Core Loss Measurement Technique
Sample Preparation

- Toroidal Shape Preferable
- Measurement of Physical Dimensions
- Calculate Magnetic Dimensions
- Selection of Winding
  - Even Distribution, full core coverage
  - Primary and Secondary 1:1, interleaved
  - Select wire size and number of turns to achieve desired Flux Density based on drive capability

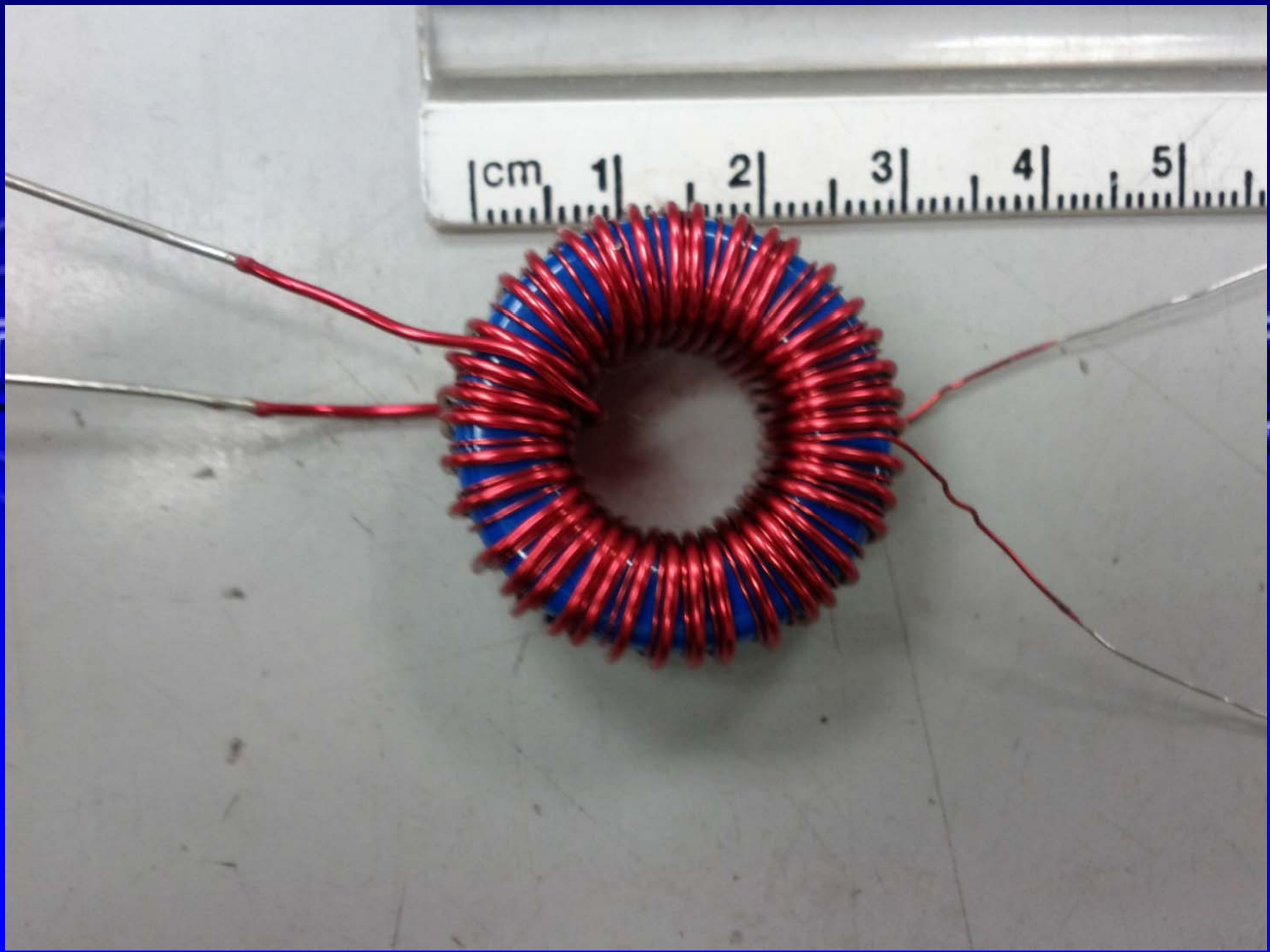
Measurement of Physical Dimensions

Painted OD	27.18	mm
Painted ID	14.80	mm
Painted Ht	11.67	mm
Paint thk.	0.17	mm
area factor	0.97	
mass(g)	26.11	grams
LTurns	44	
Wire Size	0.8	mm
L	297.9	µH

Calculation of Magnetic Dimensions

Bare Core OD	26.83	mm
Bare Core ID	15.14	mm
Bare Core Ht	11.33	mm
area(cm^2)	0.64	cm^2
PL(cm)	6.59	cm
density(g/cm^3)	6.00	g/cm^3
Permeability	125.7	

Photo of Prepared Sample



Core Loss Measurement Technique
Test Equipment

- Function Generator
- Power Amplifier
- Current Sensor
- Volt-Amp-Watt meter (or Power Meter)
- Resonating Capacitor (Optional)
- Oscilloscope (Optional)

Photo of Test Setup

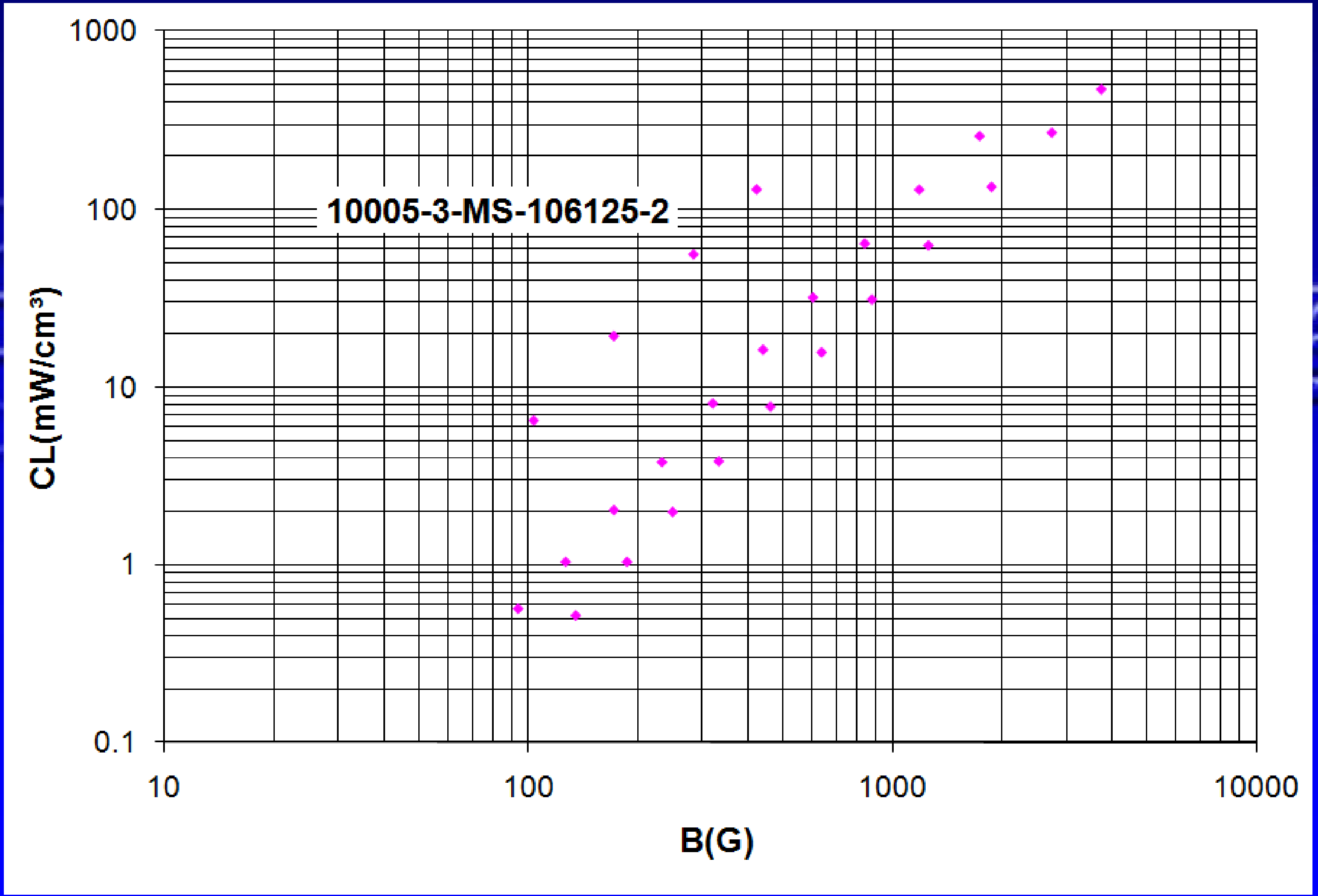
Core Loss Measurement Technique
Measuring Core Loss

- Set frequency of Function Generator
- Set amplitude of Signal
- Verify Undistorted Sinusoidal Waveform
- Record
  – Current – Optional for transformer winding
  – Voltage
  – Power Loss
  – Frequency
  – Other Parameters (Temperature, DC Bias…, etc.)

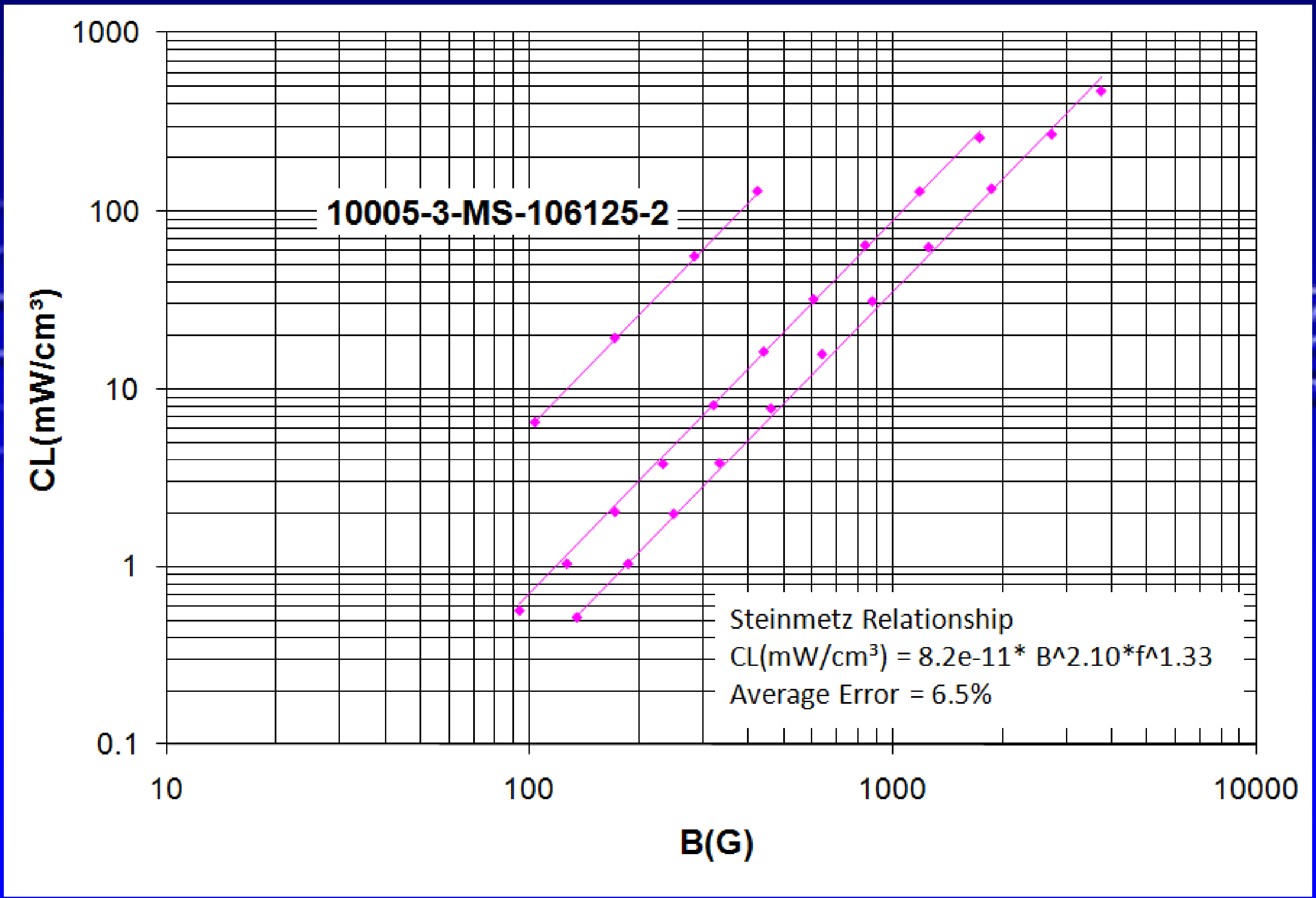
Measured Data

ID	10005-3-MS-106125-2				
area	0.642226	cm^2			
length	6.593182	cm			
N	40				
AWG	20				
f(Hz)	V(V)	I(A)	P(W)	B(G)	CL(mW/cm^3)
10000	1.54	0.0906	0.0022	135.0175243	0.519565134
10000	2.13	0.1294	0.0044	186.7450173	1.039130269
10000	2.84	0.1753	0.0084	248.9933564	1.98379415
10000	3.8	0.2357	0.0162	333.1601248	3.825888717
10000	5.27	0.3278	0.033	462.0404889	7.793477017
10000	7.28	0.4551	0.0666	638.2646601	15.72865362
10000	10.01	0.631	0.132	877.6139077	31.17390807
10000	14.29	0.908	0.267	1252.857417	63.05631404
10000	21.3	1.364	0.57	1867.450173	134.614603
10000	31.2	2.094	1.15	2735.419972	271.5908657
10000	42.6	3.044	2.01	3734.900346	474.6936001
20000	2.14	0.0639	0.0024	93.81087724	0.566798328
20000	2.89	0.0888	0.0044	126.6885211	1.039130269
20000	3.92	0.1216	0.0086	171.8404854	2.031027344
20000	5.31	0.1658	0.016	232.7737188	3.778655523
20000	7.32	0.2287	0.0344	320.8858044	8.124109375
20000	10.06	0.3147	0.0688	440.9987968	16.24821875
20000	13.78	0.4315	0.1354	604.0719105	31.97687237
20000	19.12	0.607	0.274	838.160735	64.70947583
20000	27	0.854	0.55	1183.59518	129.8912836
20000	39.5	1.274	1.1	1731.555912	259.7825672
100000	11.8	0.0755	0.0276	103.4549861	6.518180778
100000	19.58	0.1271	0.0822	171.665138	19.41284275
100000	32.4	0.2083	0.238	284.0628432	56.20750091
100000	48.3	0.3108	0.552	423.4640534	130.3636156

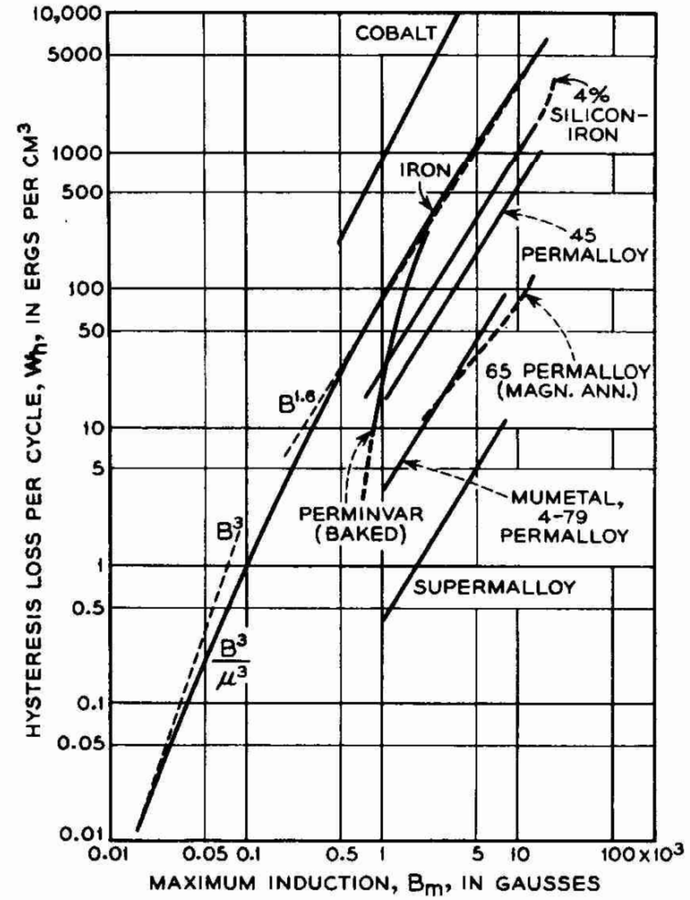
Measured Data Points



Measured Data and Fitted Steinmetz Coefficients



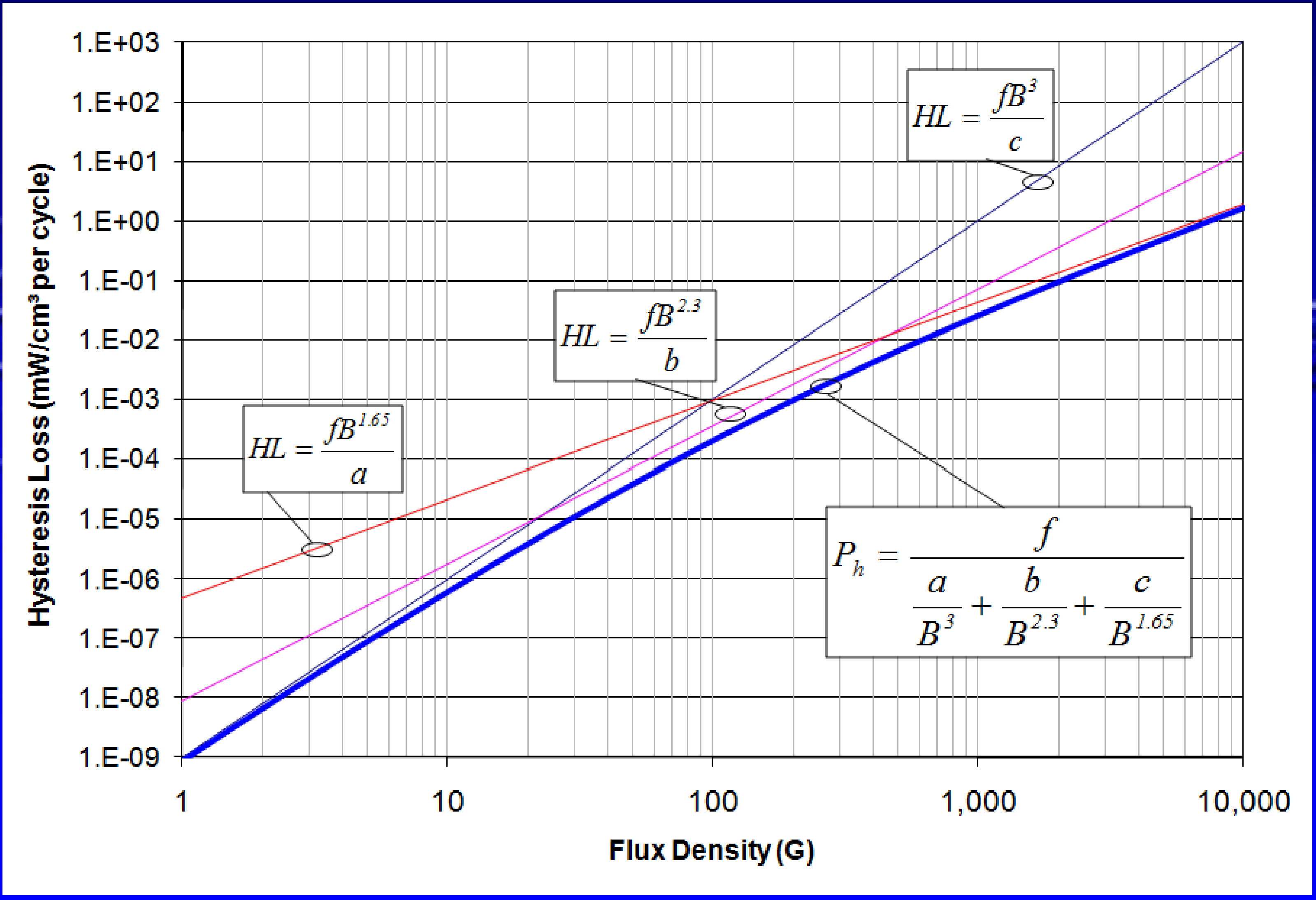
Development of Core Loss Model



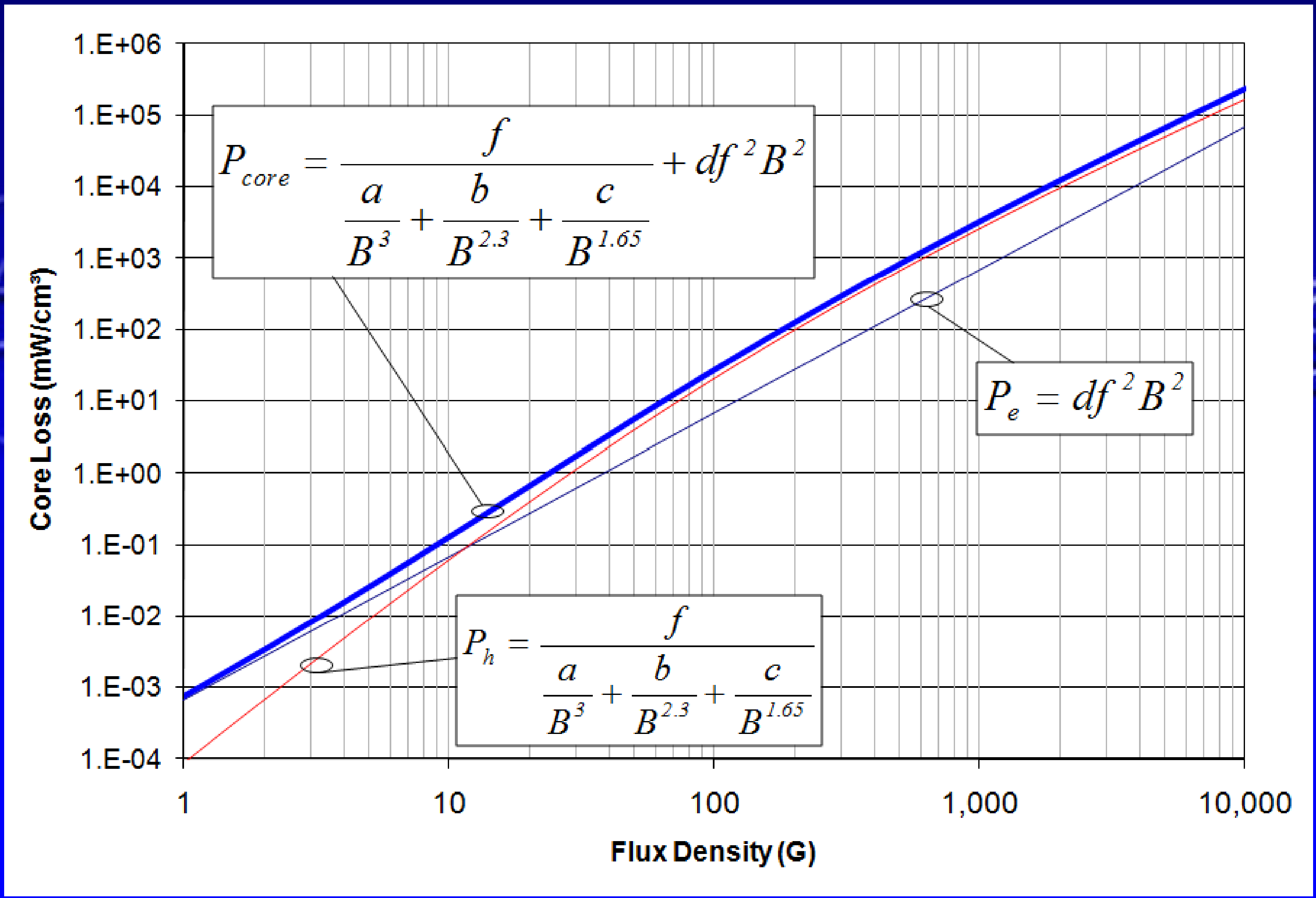
Hysteresis loss of some common materials at various maximum inductions. Note comparison with Steinmetz and Rayleigh laws.

from Ferromagnetism by Richard M. Bozorth

Development of Core Loss Model Representing the Hysteresis Loss Curve



Development of Core Loss Model Combining Hysteresis and Eddy Current Loss



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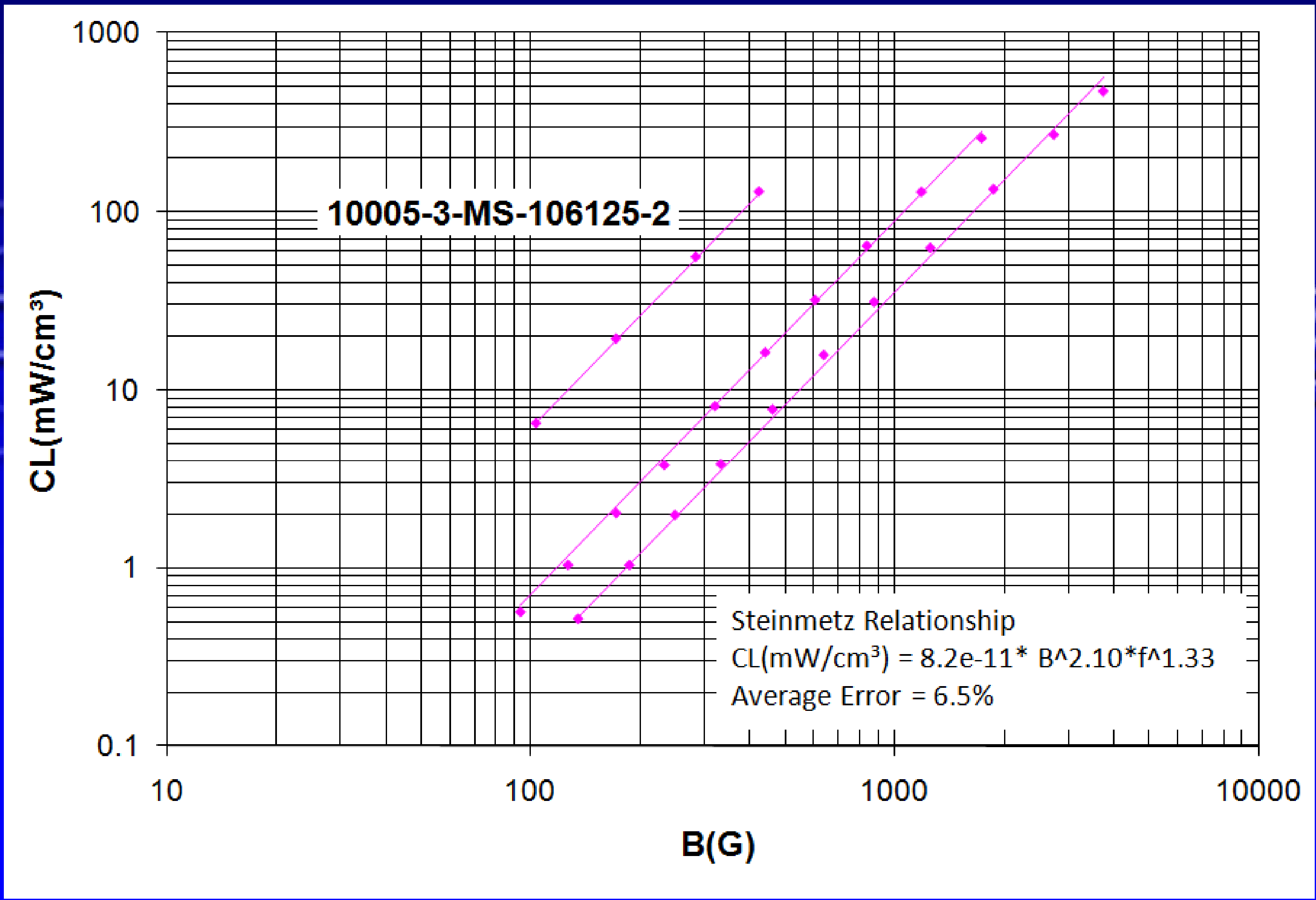
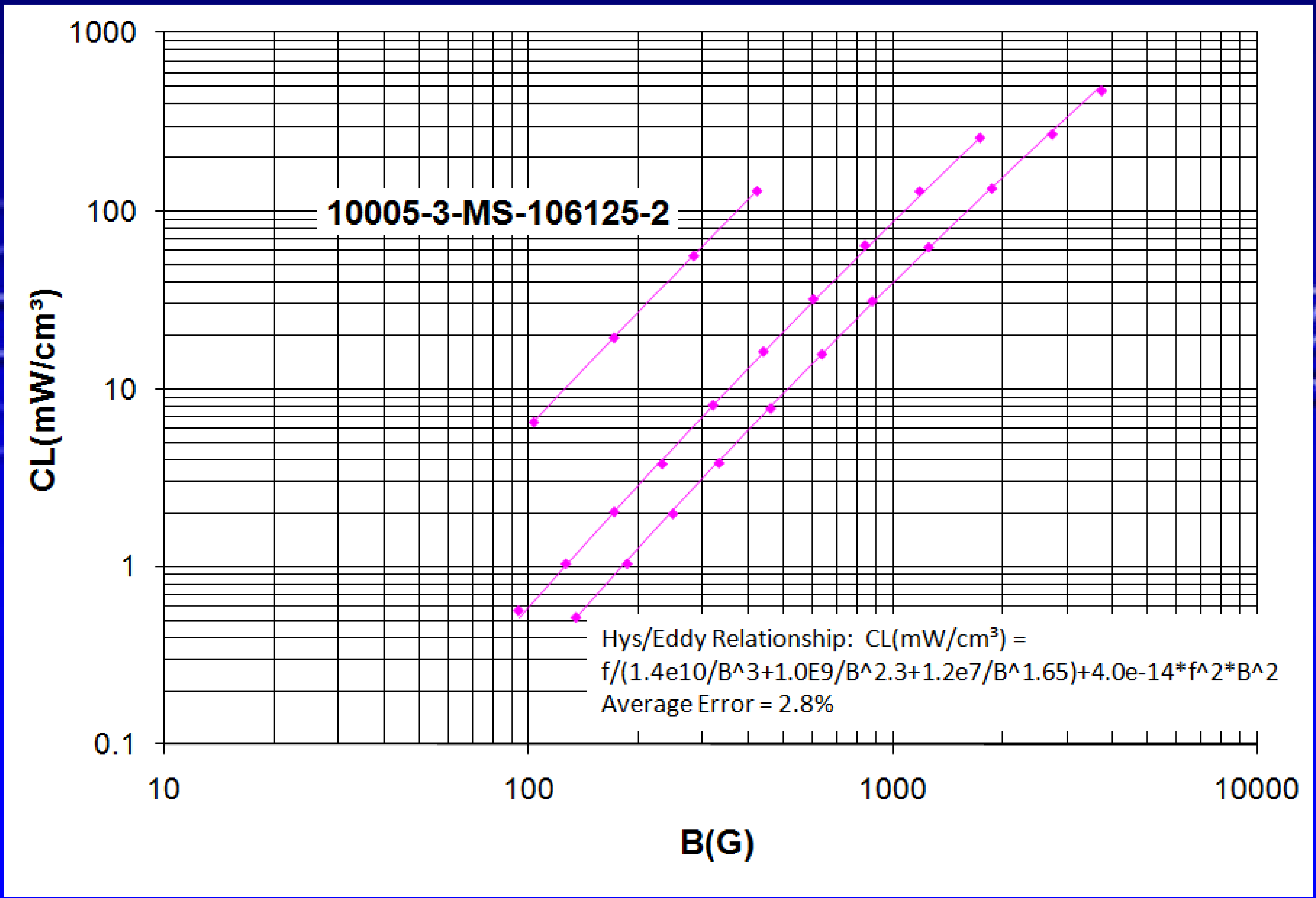


Measured Data and Fitted Hys/Eddy Coefficients



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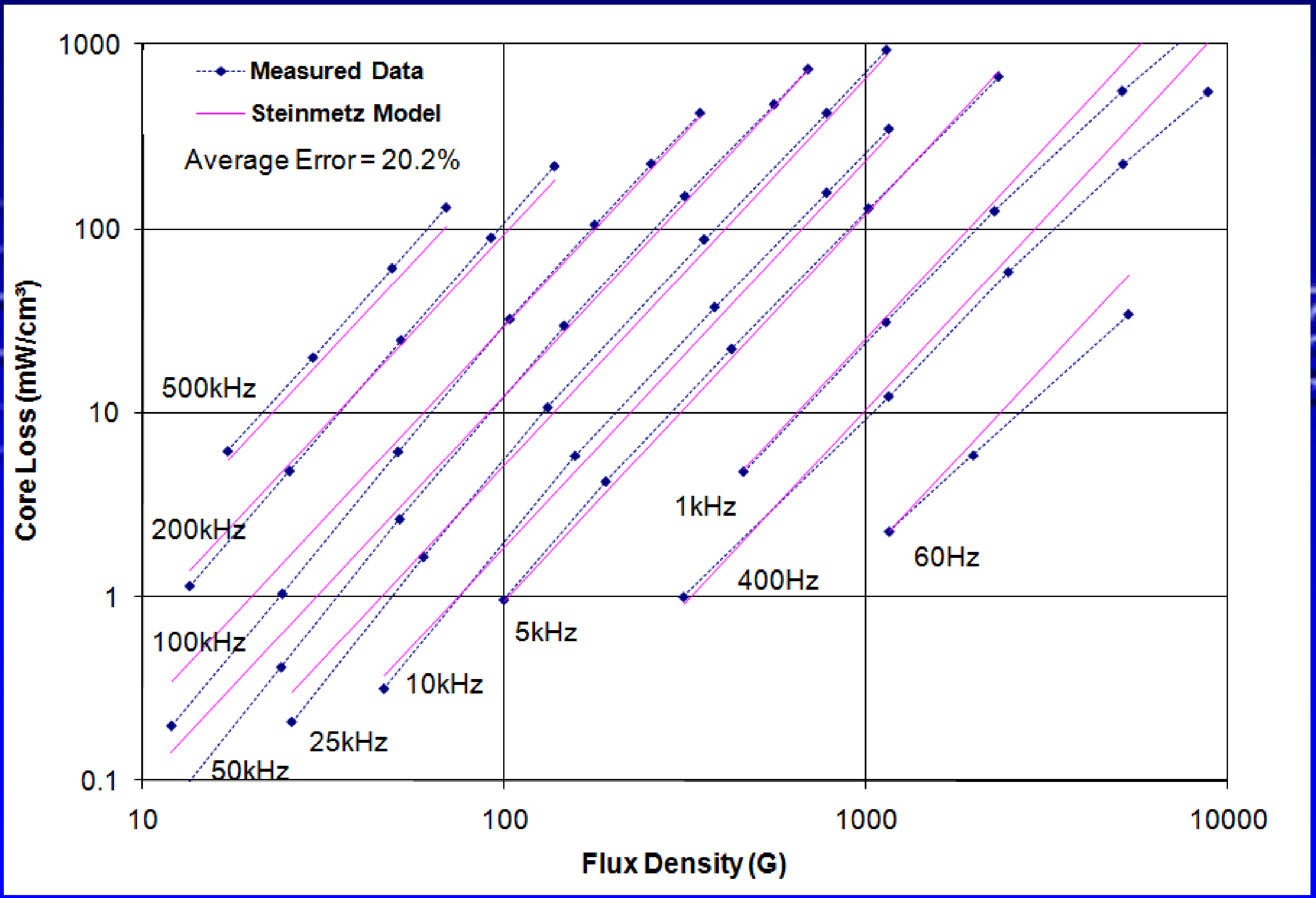

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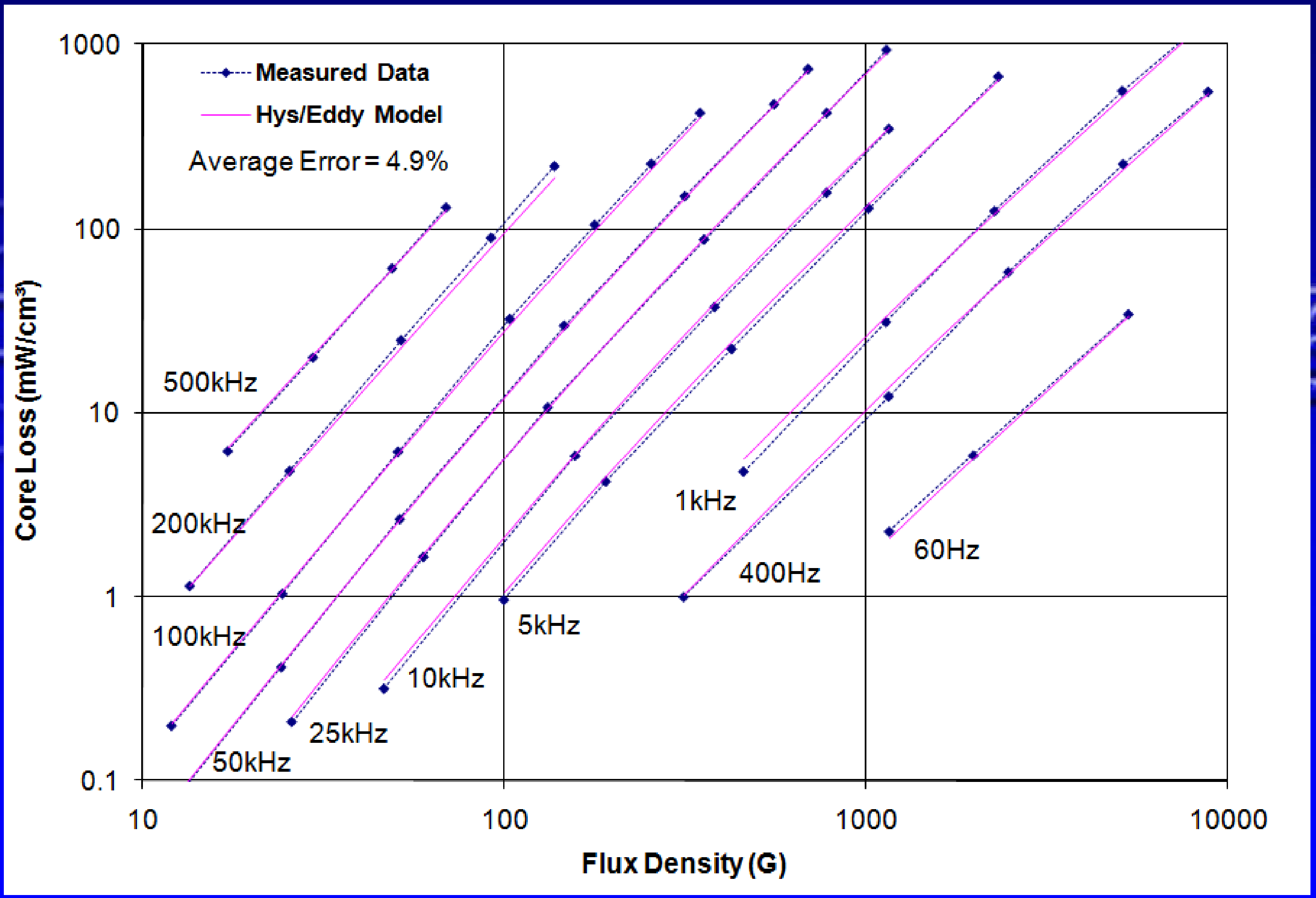


Steinmetz Model

- Advantages
  - Simple expression - Only 3 coefficients – Easily manipulated
  - Can be very accurate over a limited range of Flux Density and frequency
  - Multiple sets of coefficients can be used to increase accuracy over wider range of Flux Density and Frequency
  - Standard model used to describe Core loss of soft magnetic materials
- Disadvantages
  - Can not be extrapolated with good accuracy
  - Multiple sets of coefficients form non-continuous Core Loss equation – not "software friendly"
  - Not based on a "physical" model – Difficult to apply coefficients for physical factors such as Size, Temperature, DC Bias, and Duty Cycle

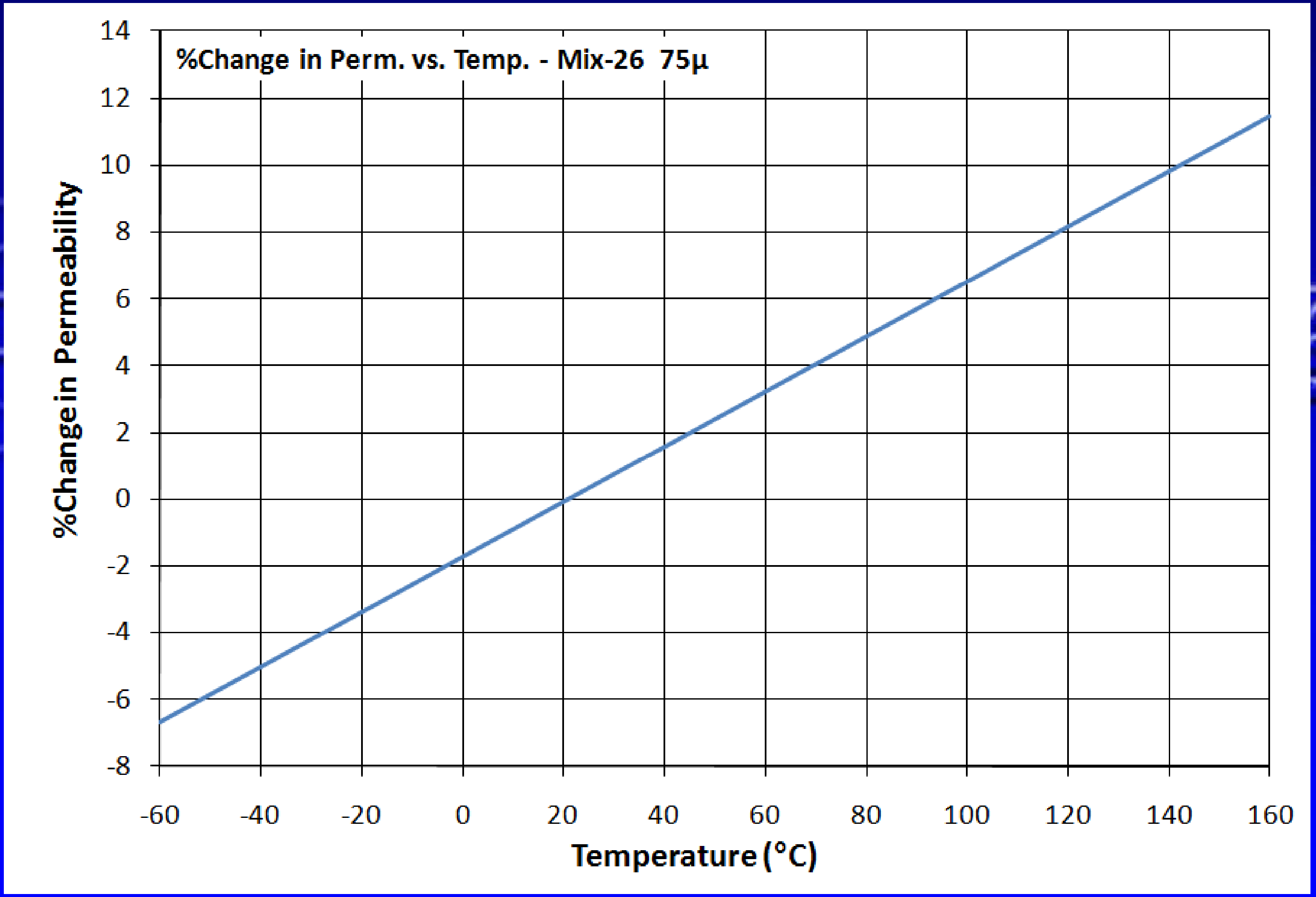
Hys/Eddy Model

- Advantages
  - One set of coefficients can be used for all Frequency and Flux Density ranges
  - High Accuracy
  - Extrapolation of data allows correlation with low signal testing
  - For any test point, the relative contribution of Hysteresis and Eddy Current Losses is known. This enables test points to be selected to isolate Core Loss coefficients
  - Separation of losses allows for intelligent modeling of other variables on losses, such as Size, Temperature, DC Bias and Duty Cycle
  - Has been applied successfully to Iron Powder, Sendust, HF, MPP, FeSi, other Powder Core materials
- Disadvantages
  - Equation is more complex - Four coefficients vs. Three
  - Not widely used

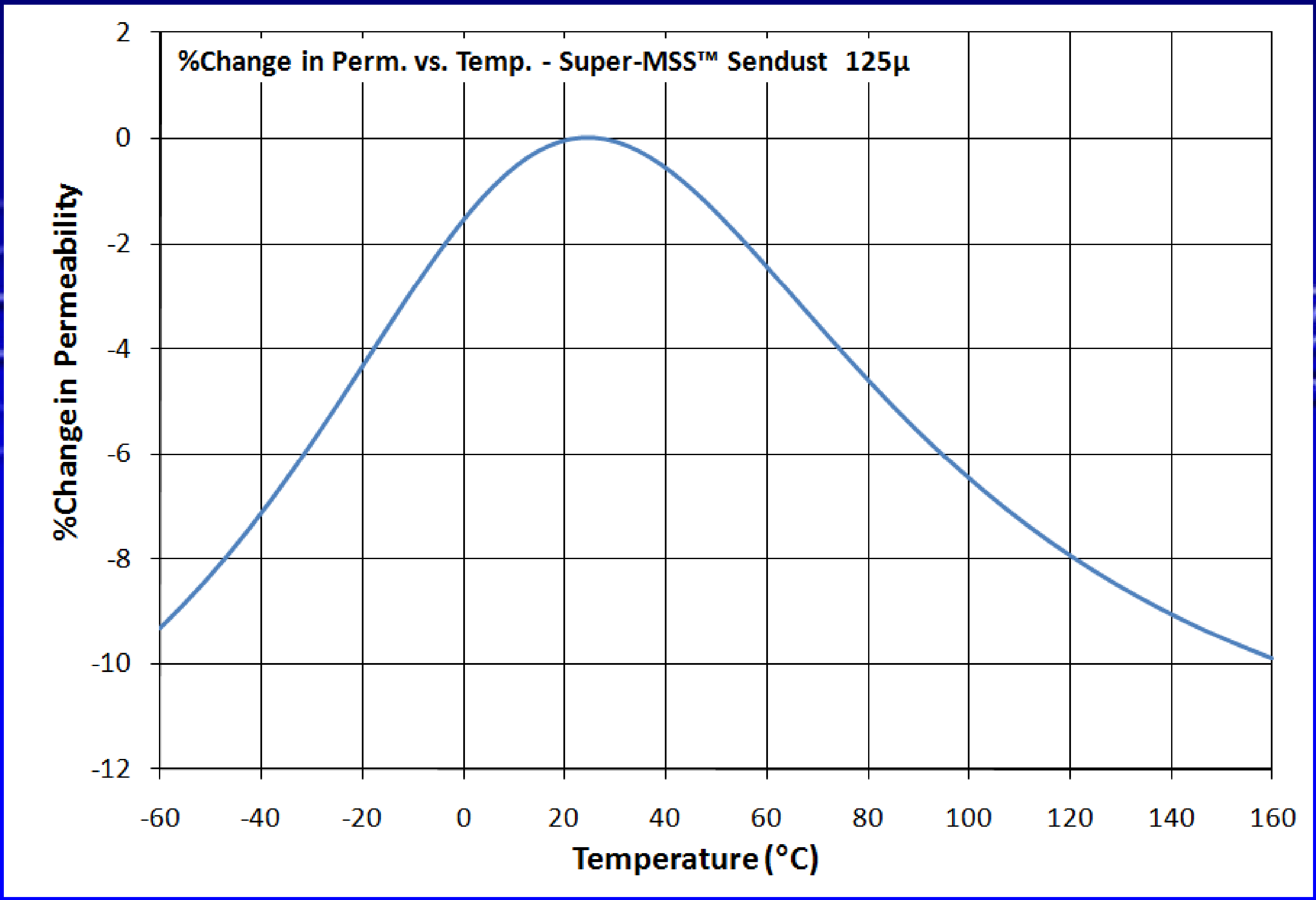
Core Loss vs. Temperature in Powder Cores Hypothesis

- Eddy Current Loss
  - Eddy Current Loss should decrease with increasing particle resistivity (linearly)
  - Most metals increase resistance with increasing temperature
  - Eddy Current loss should decrease with increasing temperature
- Hysteresis Loss
  - Hysteresis Loss will decrease with a magnetic softening of the material
  - Permeability will increase with a magnetic softening of the material
  - Permeability vs. temperature graphs are widely available for Powder Core Materials
  - For most Iron Powder Cores, Permeability increases linearly with increasing temperature
  - For most Iron Powder Cores, Hysteresis Loss should decrease with increasing temperature
  - For Other Powder Materials, Hysteresis Loss should inversely follow the Permeability vs. Temperature relationship

Permeability vs. Temperature
Mix-26 Iron Powder Core



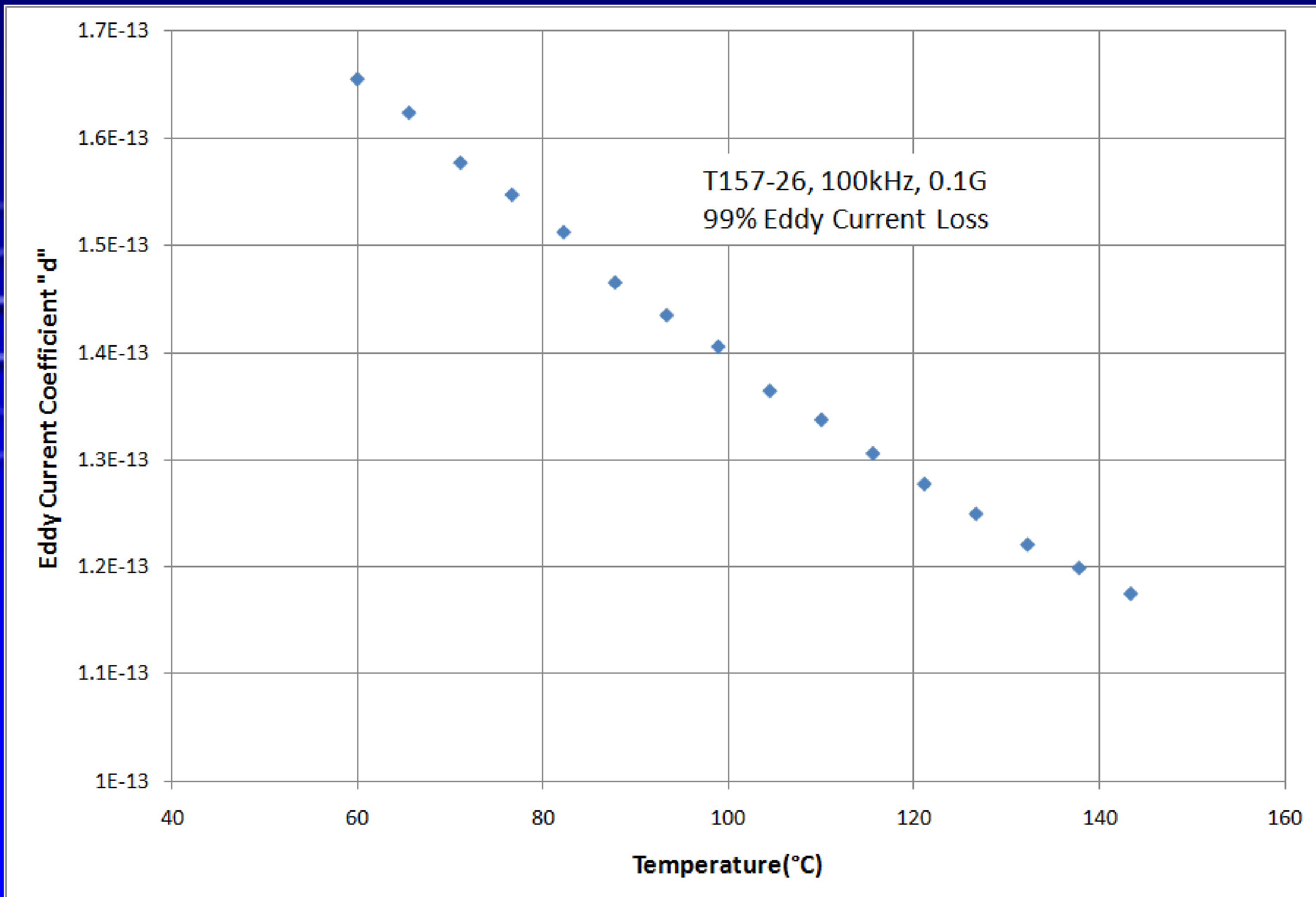
Permeability vs. Temperature
125 perm Sendust Powder Core



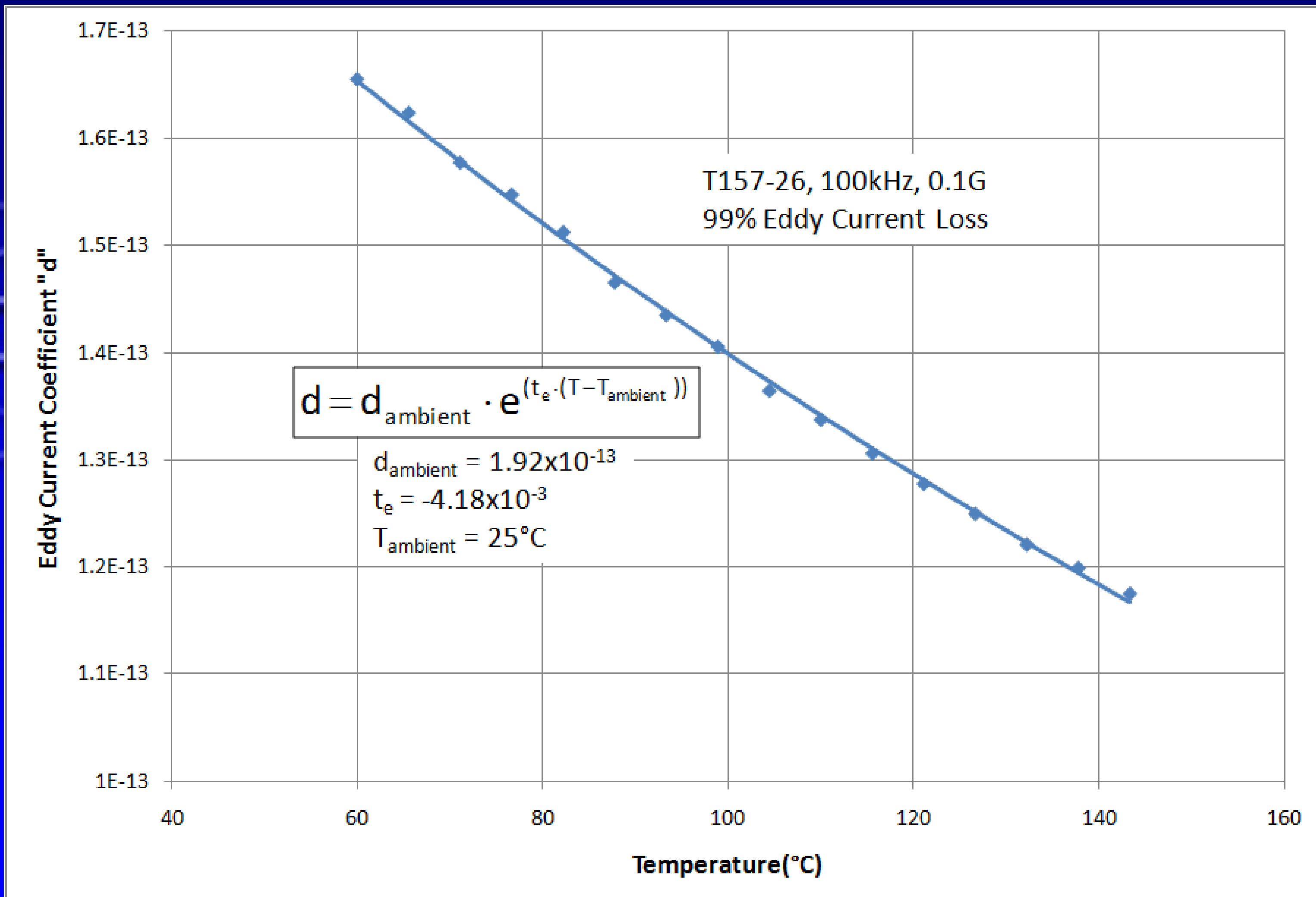
Core Loss vs. Temperature Procedure

- Pick a measurement point where Eddy Current Loss dominates the Total Loss
- Show the effect of temperature on the Eddy Current Loss.
- Pick a measurement point where Hysteresis Loss dominates
- Show the effect of temperature on the Hysteresis Loss
- Model the temperature effect for each
- Verify Model applies to entire Core Loss range

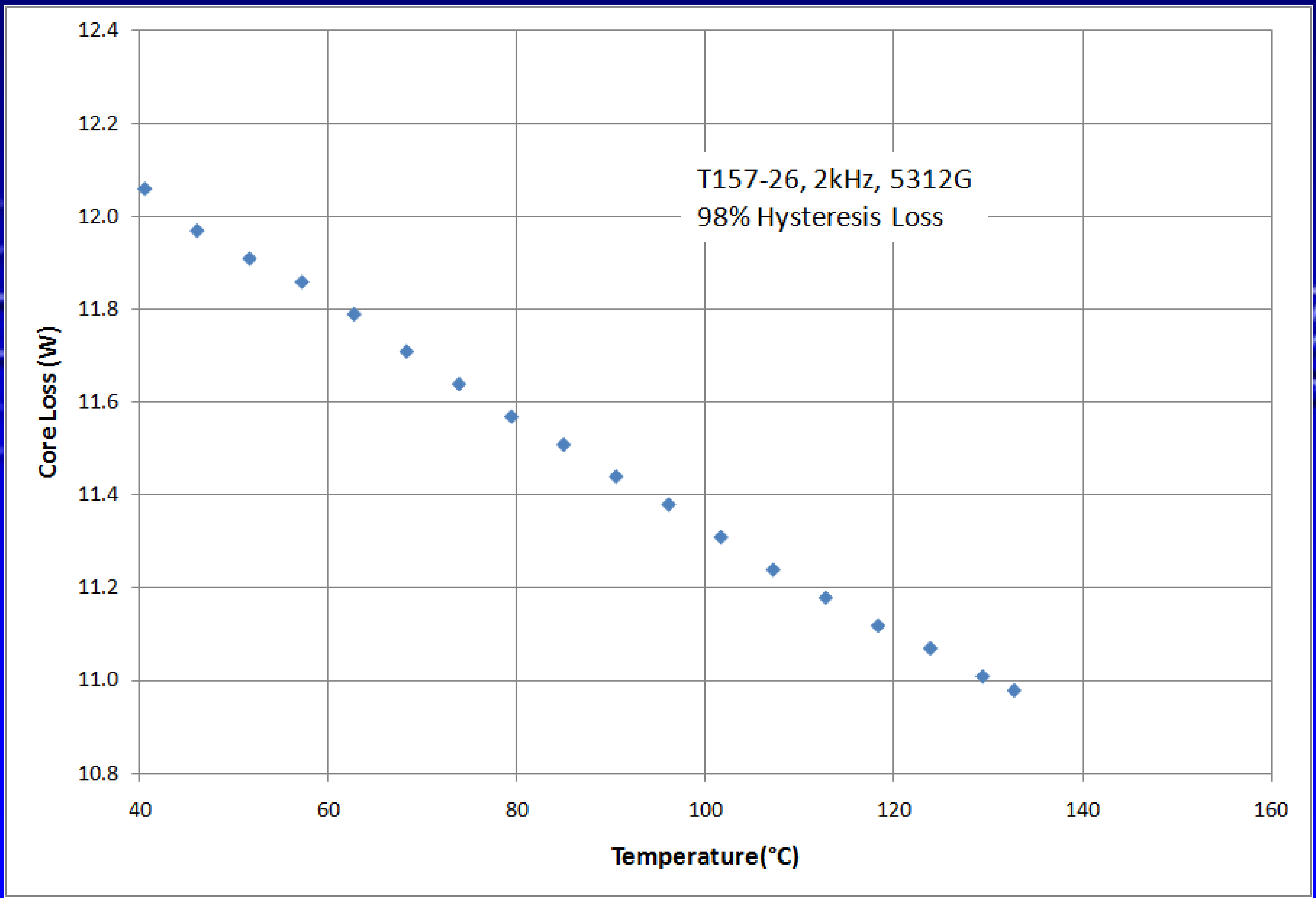
Core Loss vs. Temperature Results
Eddy Current Loss – Iron Powder Core



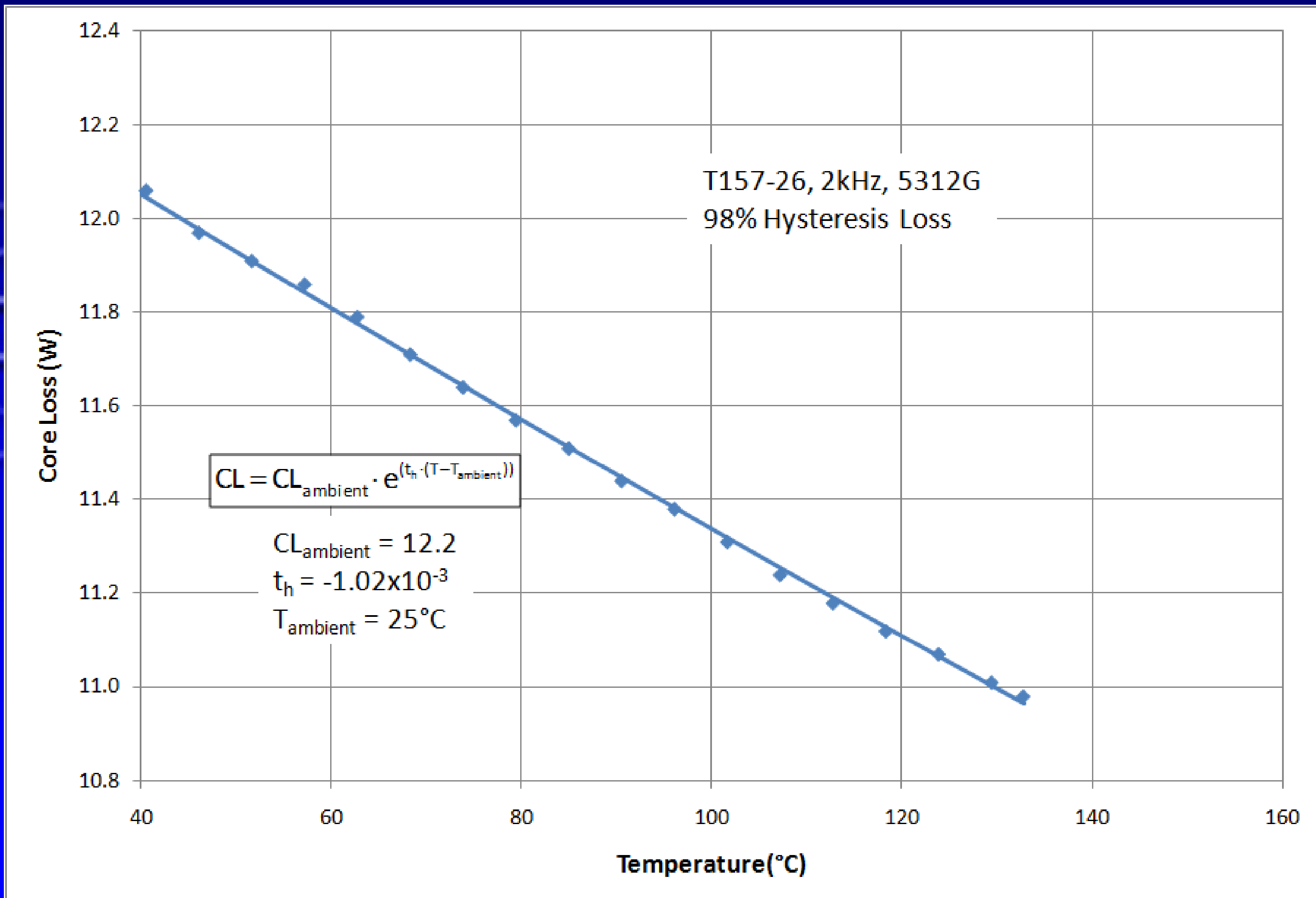
Core Loss vs. Temperature Results
Eddy Current Loss – Iron Powder Core



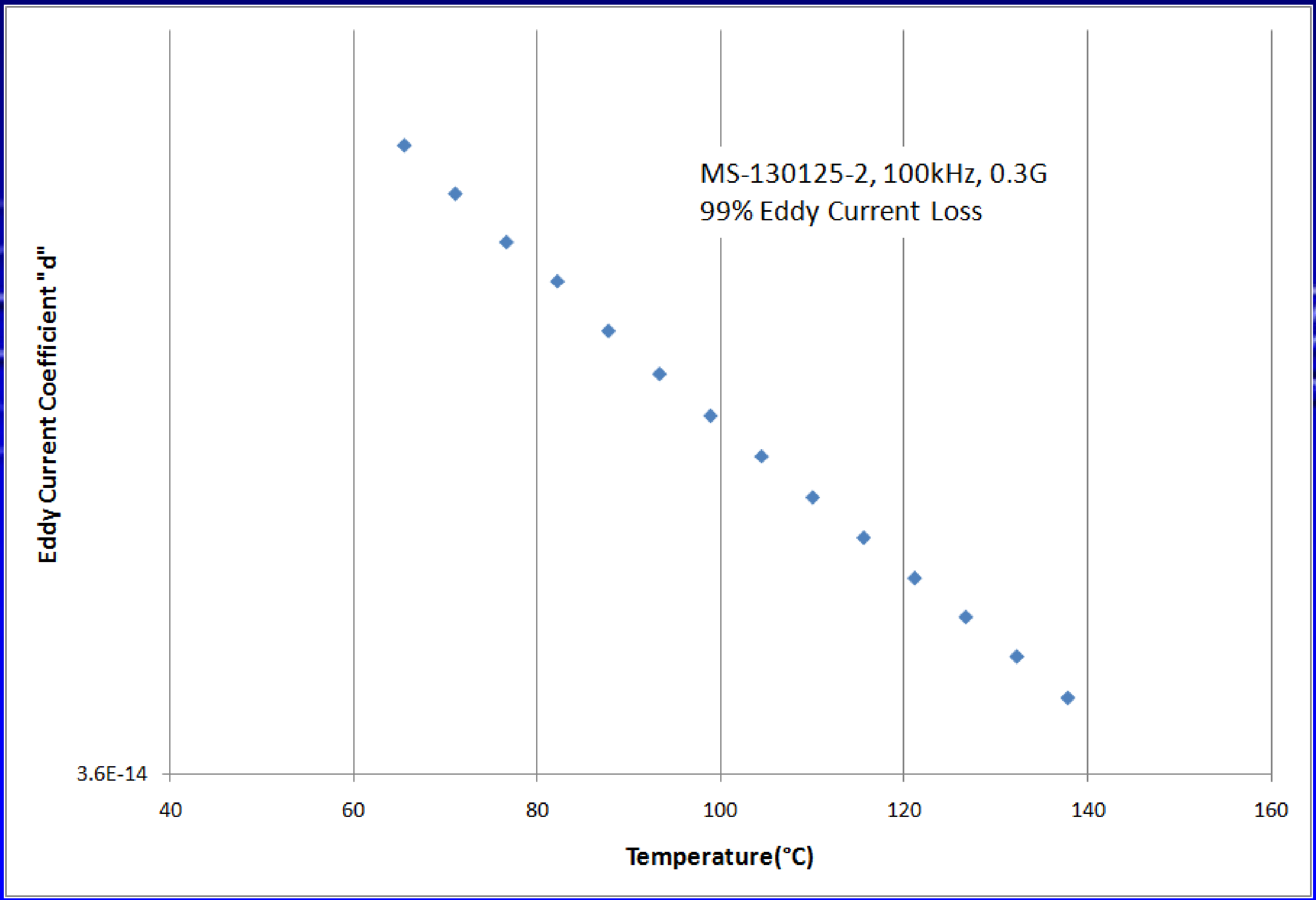
Core Loss vs. Temperature Results
Hysteresis Loss – Iron Powder Core



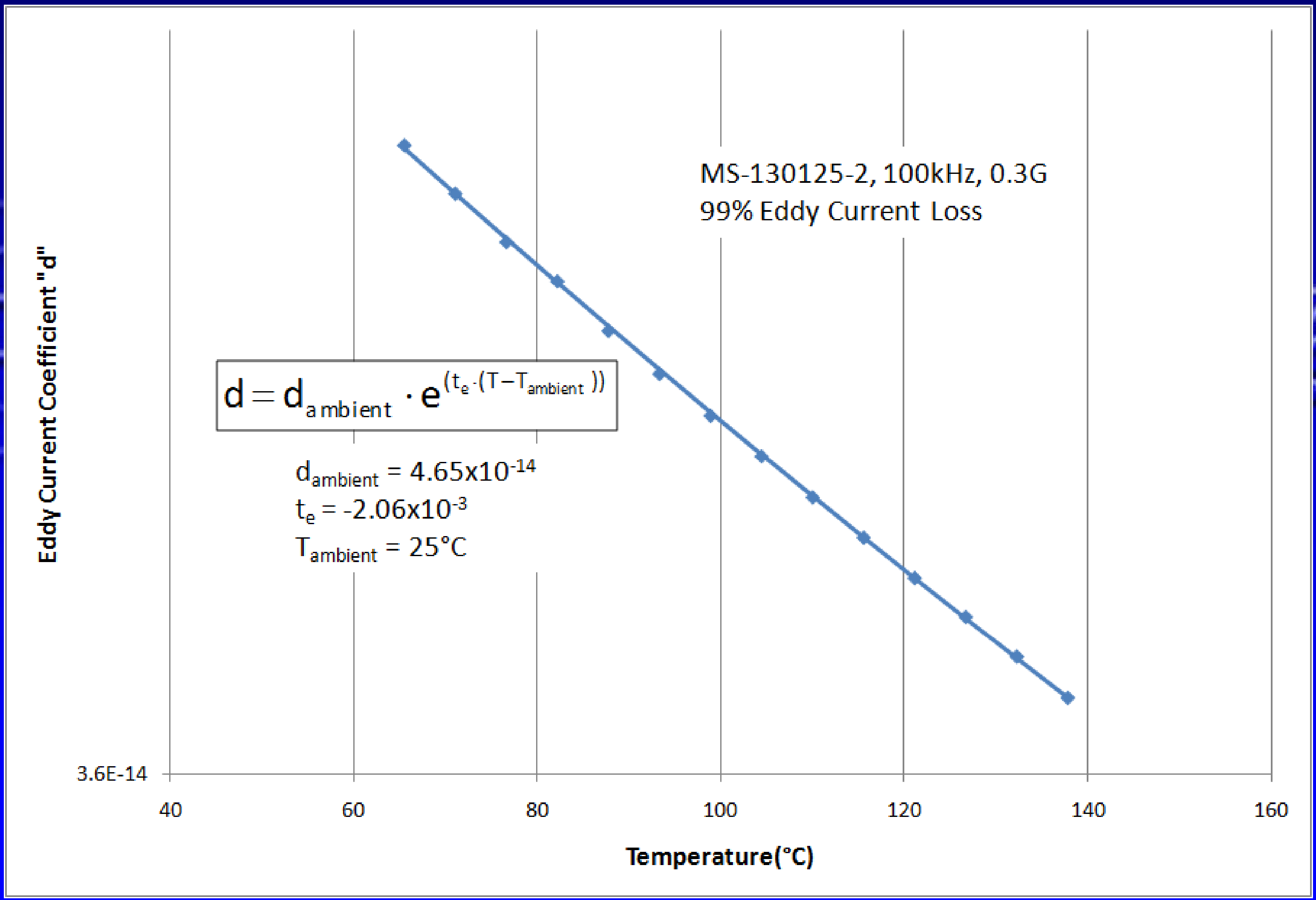
Core Loss vs. Temperature Results
Hysteresis Loss – Iron Powder Core



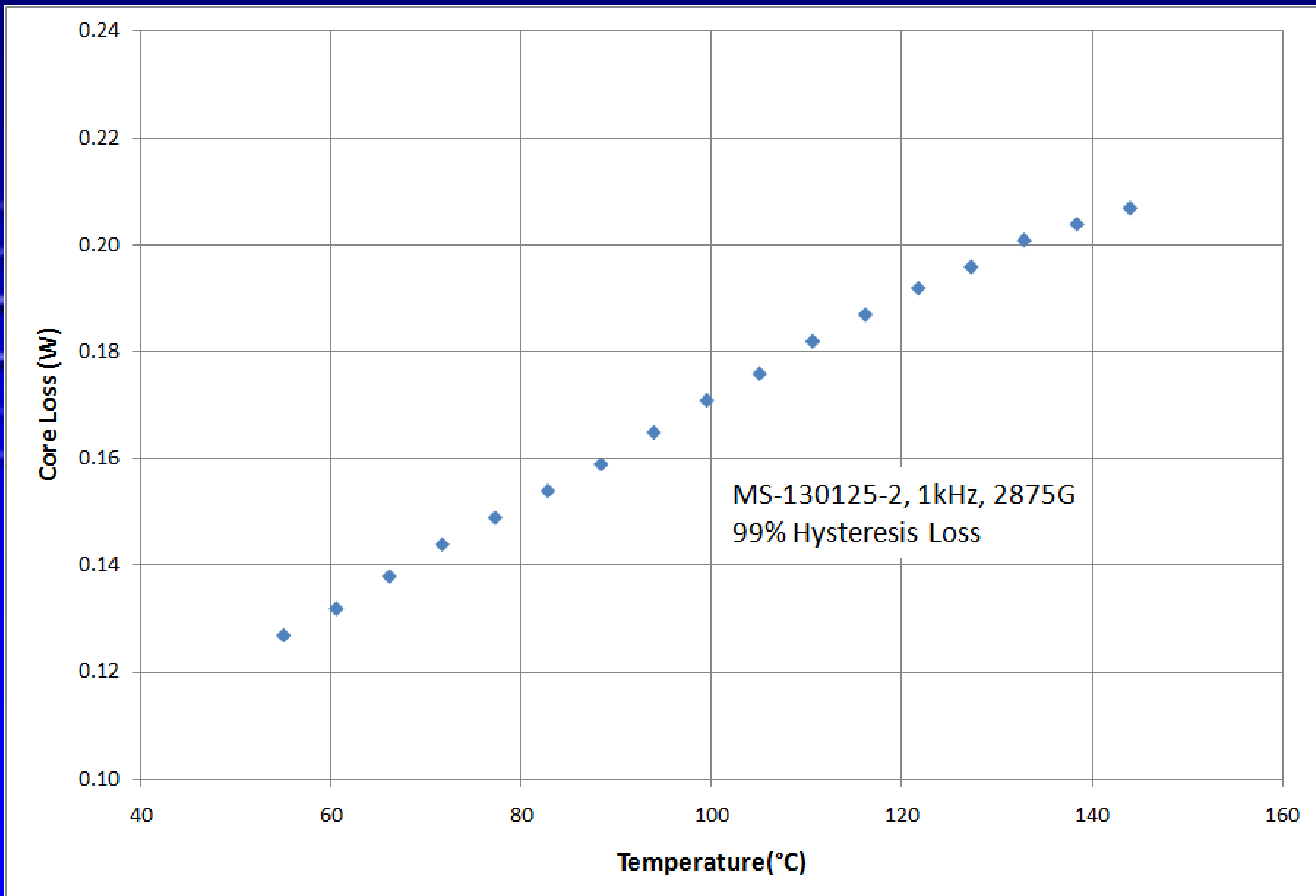
Core Loss vs. Temperature Results
Eddy Current Loss – Sendust Core



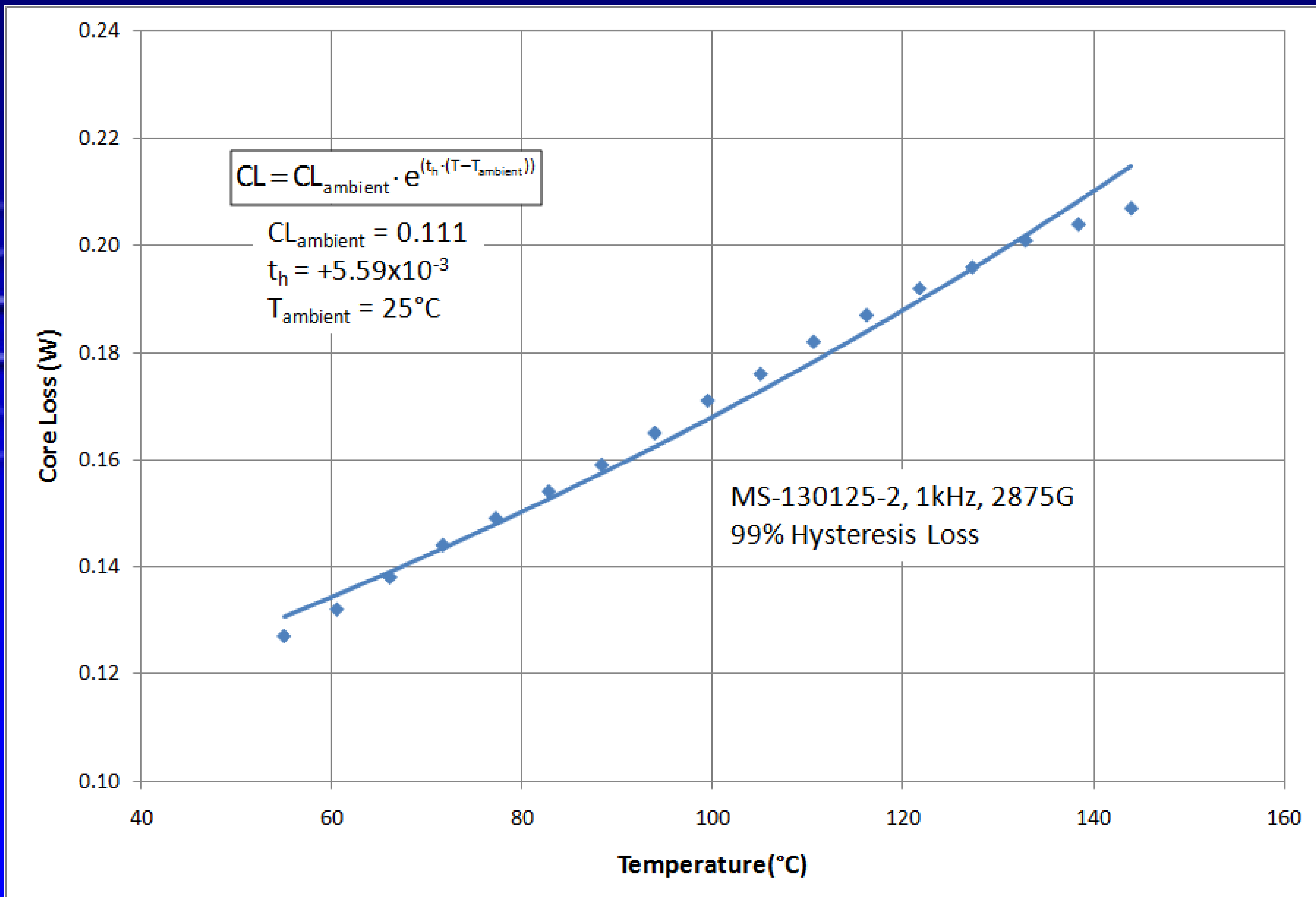
Core Loss vs. Temperature Results
Eddy Current Loss – Sendust Core



Core Loss vs. Temperature Results
Hysteresis Loss – Sendust Core



Core Loss vs. Temperature Results
Hysteresis Loss – Sendust Core



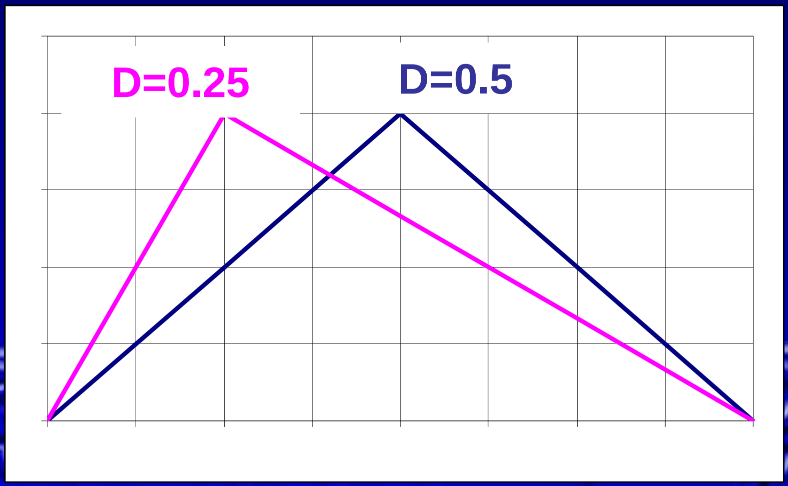
Core Loss vs. Temperature

$$CL(mW/cm^3) = \frac{f}{\frac{a}{B^3} + \frac{b}{B^{2.3}} + \frac{c}{B^{1.65}}} + d \cdot f^2 \cdot B^2$$

$$CL(mW/cm^3) = \frac{f}{\frac{a}{B^3} + \frac{b}{B^{2.3}} + \frac{c}{B^{1.65}}} \cdot e^{(t_h \cdot (T - T_{ambient}))} + d \cdot f^2 \cdot B^2 \cdot e^{(t_e \cdot (T - T_{ambient}))}$$

- Adding coefficients t_h and t_e and the variable of T allows the model to predict Core Loss vs. Flux Density, frequency, and temperature

Core Loss vs. Duty Cycle Hypothesis



- Hysteresis Loss
  - For a given swing in Flux Density, the domain walls will rotate/flip from one state to another, regardless of the time to make the transition.
  - Since the work is the same, regardless of the speed of transition, the Hysteresis Loss should be independent of Duty Cycle.
- Eddy Current Loss
  - Eddy Currents are generated in response to a changing flux. The faster the change, the higher the current that is generated.
  - For a given swing in Flux Density, a change that is twice as fast will have twice the generated Eddy Currents

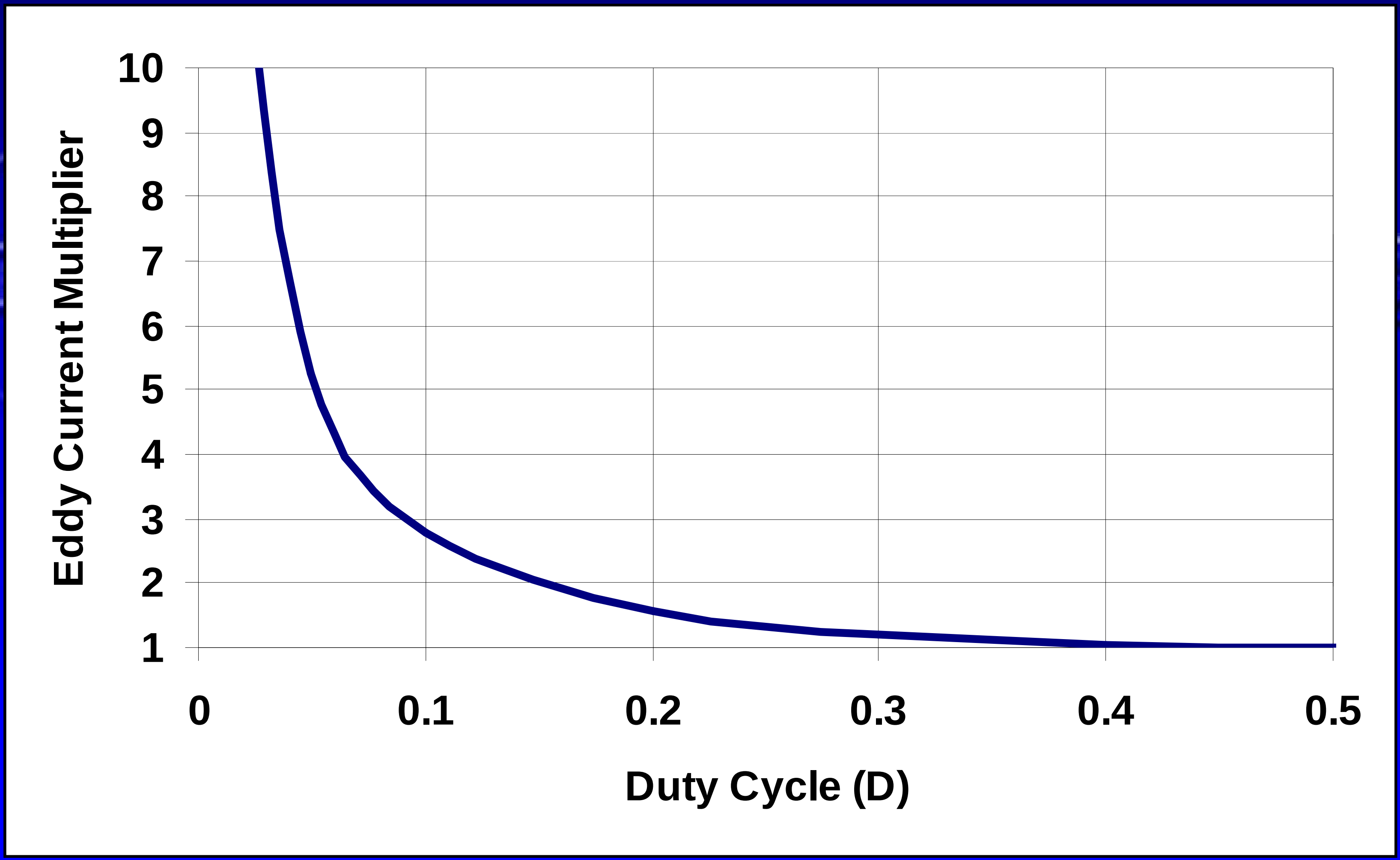
Core Loss vs. Duty Cycle

$$CL(mW/cm^3) = \frac{f}{\frac{a}{B^3} + \frac{b}{B^{2.3}} + \frac{c}{B^{1.65}}} + d \cdot f^2 \cdot B^2$$

$$CL(mW/cm^3) = \frac{f}{\frac{a}{B^3} + \frac{b}{B^{2.3}} + \frac{c}{B^{1.65}}} + d \cdot f^2 \cdot B^2 \cdot \frac{1}{4}\left(\frac{1}{D} + \frac{1}{1-D}\right)$$

- Duty Cycle term assumes that the losses of sinusoidal measurements correlate well when D=0.5
- The relative contribution of increased losses due to duty cycle are dependent on the relative contribution of Eddy Current Losses
- Duty Cycle relationship needs to be verified by measurement

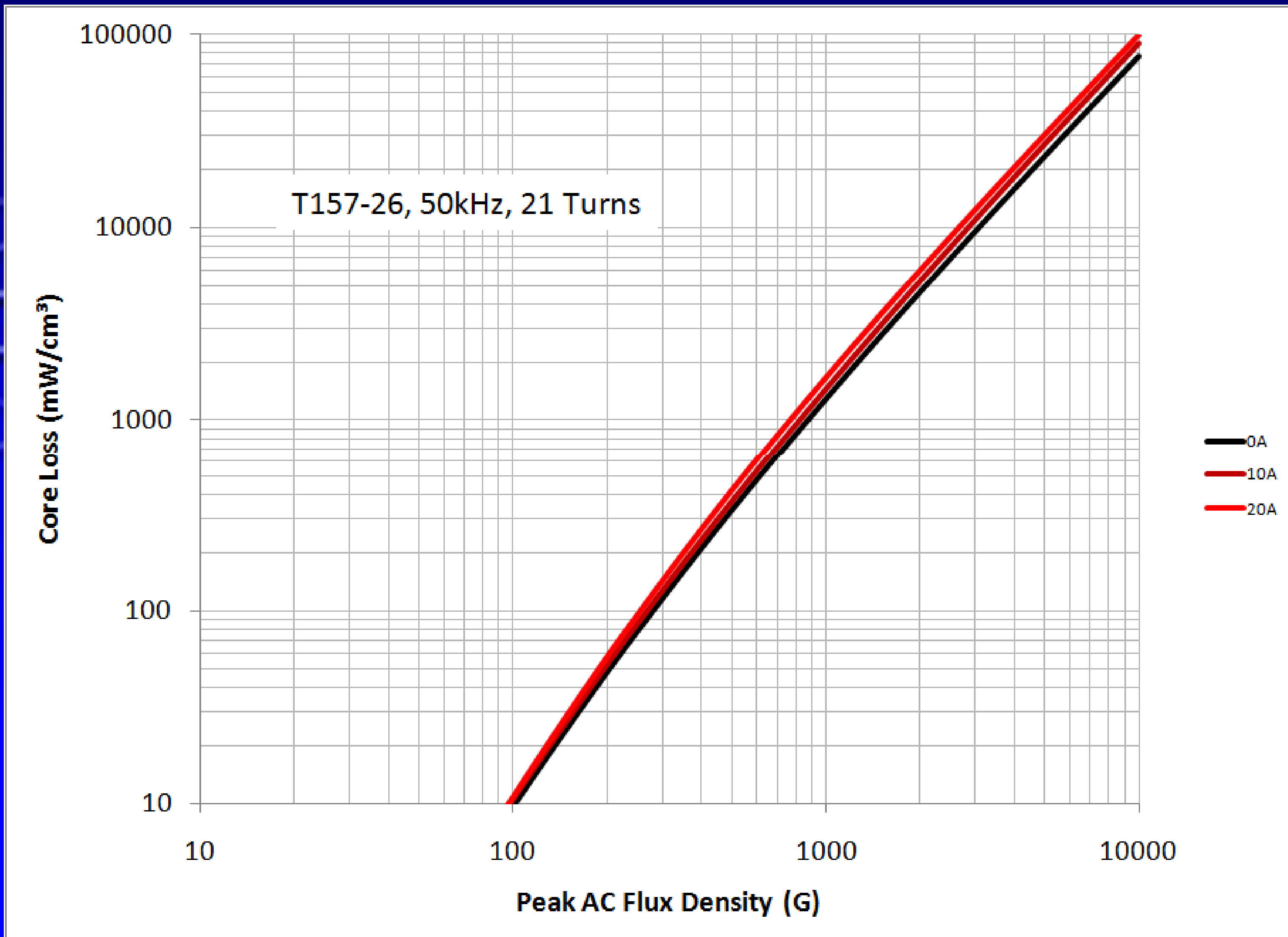
Core Loss vs. Duty Cycle
Eddy Current Multiplier vs. Duty Cycle



Core Loss vs. DC Bias
Hypothesis

- Eddy Current Loss
  - Eddy Current Loss is dependent on changing Flux Density and Electrical Resistance of the magnetic material.
  - DC Bias does not impact the Electrical Resistance of the magnetic material.
  - Eddy Current Loss will be independent of DC Bias
- Hysteresis Loss
  - Hysteresis Loss is dependent on the relative ease/difficulty of Domain Wall movement
  - As a material is Biased, the domains walls are shifted to a more stressed position
  - Additional shifting of the domain walls will become more difficult as the biasing level increases
  - Hysteresis Loss should increase significantly with DC Bias
  - Hysteresis Loss coefficients a, b and c will likely be impacted differently by DC Bias

Core Loss vs. DC Bias Results
Preliminary Test Results



Summary

- Core Loss technique discussed
  - Sample preparation
  - Testing Procedure
  - Recording of results
  - Fitting of Models
- Applied different Core Loss models to the data
- Discussed the merits of different Core Loss models
- Discussed application of the Hys/Eddy Current Core Loss model to describe the effect the variables such as Temperature, Duty Cycle and DC Bias had on Core Loss

Future Work

- Evaluate Alternate methods of Core Loss evalulation
  - Resonant Decay
  - Square Wave Testing
- Verify Core Loss vs. Duty Cycle Relationship
- Further investigate Core Loss vs. DC Bias – develop relationship
- Develop single Core Loss model that incorporates Flux Density, frequency, Temperature, Bias, Duty Cycle, Geometry

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