AMPED ADVANCED MAGNETICS FOR POWER & ENERGY DEVELOPMENT

Magnesil Material Datasheet

Prepared for:	CBMM North America
CBMM	1000 Omega Drive Pittsburgh, PA 15205

Description of Core Under Test (CUT).

Magnetics, Inc. 015500554K is a tape would core with a composition of silicon-iron, grain oriented of about 3%, commercially known as Magnesil. Applications for Magnesil include, and are not limited, to power transformers, current transformers, high power reactors, and magnetic amplifiers. Has a saturation flux density that ranges from 1.5 – 1.8 T. Due to exhibiting a high Curie temperature, it would be desired for devices that are exposed between 200°C and 500°C. The saturation flux density is usually between 1.5 and 1.8 T.

Test Facility	
Test Laboratory	AMPED
Address	1435 Bedford Avenue
City, State, Zip Code	Pittsburgh, PA 15219
Phone	412-802-0988
Fax:	412-802-0779
Website:	www.engineering.pitt.edu/AMPED

Test Personnel	
Name	Chris Bracken
Title	Research Associate
Signature	

Datasheet Revision History			
Revision	**Date**	**Description**	**Revised By**
N / C	Date of Release	Initial Release	CSB (Initials of Revisor)

Declaration of Sufficiency

The following results for the Core Under Test fulfill requirements of best effort of capability based on standards and manufacturer representative data. Results are subject to the following conditions:

The results are within margin of the of the calculated raw values obtained via experiment.
The results are within a reasonable margin of reported data from the manufacturer or other facilities.

The result has been evaluated by Test Personnel and Supervisors under quality procedures and shown here in the datasheet. It is understood that the results shown are subject to repeatability and third-party testing analysis, encouraging debate and transparency amongst testing personnel.

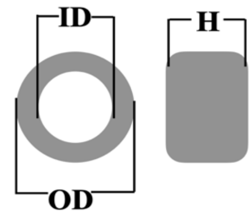
The test facility noted as where the testing was conducted is also responsible for this declaration.

Person(s) responsible for finalizing the marking of this declaration, approving of best effort of capability:

Name	Title	Date
PAUL R. OHODNICKI, JR., PHD	**Associate Professor**	**22-Aug-22**
RICHARD B. BEDDINGFIELD, PHD	**Postdoctoral Research Scholar**	**22-Aug-22**

Core Specifications

Dimensions			
Description	**Symbol**	**Sample Dimension (mm)***	**Actual Dimension Used (mm)***
Core Inner Diameter	ID	35.3	38.1
Core Outer Diameter	OD	53.02	50.8
Core Height	H	15.21	12.7



*Sample Dimension refers to the dimensions that include coating. These dimensions do not pertain to the effective area used, as this effective area was stated in the provided core manufacturer datasheet. A correction factor accounts for this where plausible, taking the ratio of Sample Dimension-to-Actual Dimension, multiplying the cross-sectional area with this term (See AMPED standard AMP-STD-0C for this calculation, and for other calculations).

Magnetic Characteristics				
Description	**Symbol**	**Finished Dimension**		**Unit**
Effective Area	A_e	68.9		mm^2
Mean Magnetic Path Length	L_m	139.6		mm
Core Mass	C_M	0.07358107		kg**
Density	D	7650		kg / m^3
Lamination Thickness	L_M	0		µm
Chemistry	Si-Fe		**Grade**	
Anneal			**Impregnation**	Unimpregnated
Core Supplier	MAGNETICS		**Part Number**	01500554K
Wire Supplier	Remington Industries		**Wire Gauge**	25 AWG

Unless explictly noted by the manufacturer, the **Core Mass shown was calculated multiplying the Effective Volume (the **Effective Area** multiplied **Mean Magnetic Path Length**), and the provided **Density** by the manufacturer, all in this table. The **Density** was provided from the manufacturer provided documentation *"2016-Magnetics-Tape-Wound-Cores-Catalog"*.

Configuration

Core Testing. Testing performed using the configuration changes as noted, used to complete the evaluation. The actual test parameters are specified in the Setup, the Test Procedure and the Data Presentation sections.

Configuration Number	Frequency Range	Primary Turns (N_P)	Secondary Turns (N_S)
1	60 Hz – 50 kHz	8	8

Note: The choice of primary and secondary turns was chosen such that estimates the probe and core saturation points by the relation defined in IEEE-393 and IEC 62044-3: $N_P = H_e\, l_e/i$, and $N_S = V_{rms}\ / k\ f\ A_e\ B_e$. k is dependent on the waveform in question, f is frequency of each test, A_e is core effective area, B_e is the saturation flux density, V_{rms} is 90% of the maximum voltage the probe is rated for at the givien setting it takes the measurement, i is 90 percent of the current the current probe is rated for, H_e is the estimated value the setup can provide for field strength (assumed 1000 A / m), and l_e is the mean path length of the core.

Section One: Room Temperature Environmental Measurements. Magnetic Core Characterization Testing: Test Procedures and Results.

Purpose.

This test procedure is used to measure the B-H Curves, core losses, and permeability of the core under test at room temperature.

Test Equipment.

The test equipment shall be used as follows:

Lab Asset No	Description	Manufacturer	Model No	Serial No
WAV0003	Arbitrary Waveform Generator	Keysight Technologies	EDU33212A	CN61310043
AMP0001	High Speed Power Amplifier	NF Electronic Instruments	4025	4025-112
OSC0003	Oscilloscope (500 MHz)	Keysight Technologies	MSOX4054A	MY61260112
PRO0003	10:1 200 MHz Differential Probe	Keysight Technologies	N2792A	PH61260009
PRO0009	Differential Probe	Rigol	RP1100D	20180742
PRO0005	AC / DC Current Probe	Keysight Technologies	1147B	JP61071359
CAP0001	5 uF Capacitor	Cornell Dubilier Electronics (CDE)	SCRN244R-F	None
CAP0002	5 uF Capacitor	Cornell Dubilier Electronics (CDE)	SCRN244R-F	None
RES0001	5 Ohm Resistor	Riedon	UB15-5RF1	None
LAB0001	Computer	AMPED	None	None

Test Procedures.

I. Core Loss Testing - Low Signal with Amplifier Setup – Room Temperature – Manual Procedure.

Per AMPED Standard AMP-STD-001, below is the procedure for manual operation of equipment for the Low Signal Setup, to be applied as follows. For a more detailed and general procedure to apply the test, refer to the referenced standard described here.

a. Turn on the measurement equipment and allow sufficient time for stabilization (e.g. 20 minutes).

b. Set the Arbitrary Waveform Generator to the following settings.

- Begin with a low signal.
  - Frequency. Set frequency as initial starting point at 60 Hz. Increment based on the desired frequencies necessary to perform measurements.
  - Amplitude. Begin with an amplitude value, in terms of peak-to-peak (V_{PP}), at 10 milli. Increase where deemed appropriate to make sure a fully functioning signal is observed in an acceptable tolerance.

c. Set the Power Amplifier values.

- Be sure to press input cable connected to on (usually A).
- Press the desired gain. Performed in these tests at “X50”.

d. Set the Oscilloscope to the following settings.

• Specify Probe Attenuation.

• Measurements were performed with a Keysight 1147B Current Probe has a fixed attenuation ratio of 0.1 V/A and cannot be changed.

• Voltage Probe from Keysight, the N2792, was used for measurements, and has fixed attenuation ratio of 5:1 after calibration with oscilloscope. Probe with Asset Number PRO0003 was used to acquire data from 60 Hz – 1 kHz.

• Voltage Probe from Rigol, the RP1100D, was used for measurements, and has fixed attenuation ratio of 100:1 after calibration. Probe with Asset Number PRO0009 was used to acquire data from 10 – 50 kHz.

• All data, 60 Hz – 50 kHz , was captured with High Resolution Settings under Waveform-Acquire Menu.

e. Turn output of Arbitrary Waveform Generator on.

f. Level the output voltage at the offset adjust with flat head screw driver, if possible. Note if probe does not have that capability.

• For data presented, Voltage probe with asset number PRO0009 does not have the capability.

g. Examine the Waveform on the Oscilloscope read from the Current Probe on the input side and the Differential Probe on the Output Side.

• Be sure to capture 3 - 5 periods of the excitation signal being applied.

• Look for point of saturation for the core. This can be visually examined when the waveform's maximum value no longer increases. Sine and Ramp waveforms flatten, Square becomes more in a curve. See Data Presentation for examples.

• Magnetic Flux Density is optional for oscilloscope waveforms but recommended.

h. Auto zero and Degauss the Current Probe before step i. Also Degauss where Average Current Waveform value climbs above an acceptable tolerance of +/- 10 mA.

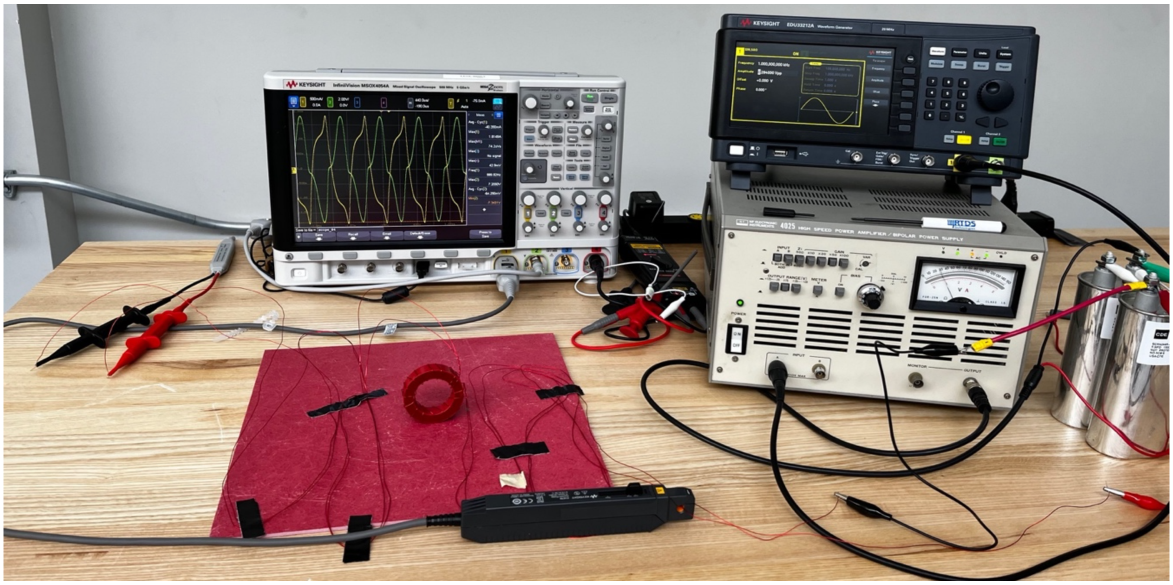
i. Setup included correction components for DC Biasing part of the setup. See the test setup section for a diagram. Note a 5 Ohm Resistor was in series with two 5 µF Capacitors in parallel.

j. Repeat steps a - f for Square Waveform, Ramp Waveform, or other excitation waveforms for examined interest.

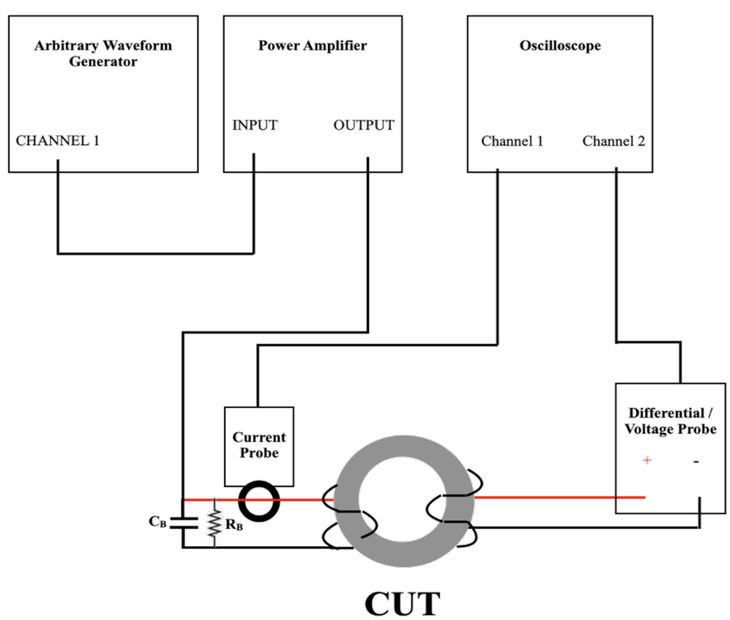
k. Record relevant data for Data Presentation.

Setup.

Core Testing. Configure the test equipment as shown below, with one figure showing the actual test setup, and another as the block diagram.



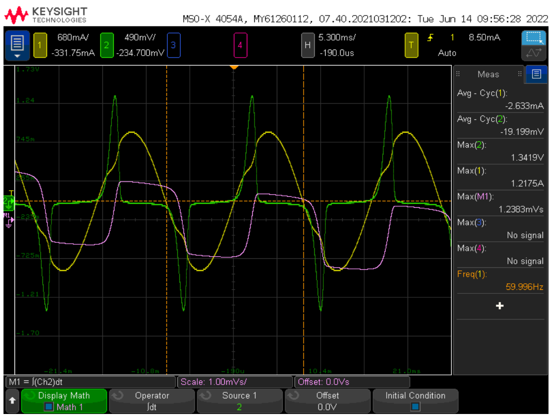
Core Loss Testing - Low Voltage with Amplifier. Typical Test Setup.

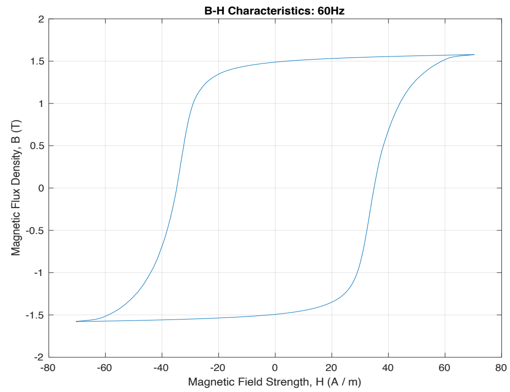


Core Loss Testing - Low Voltage with Amplifier. Typical Test Setup: System Block Diagram.

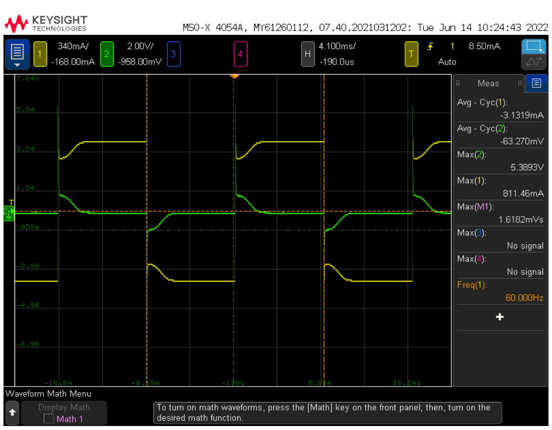
Data Presentation.

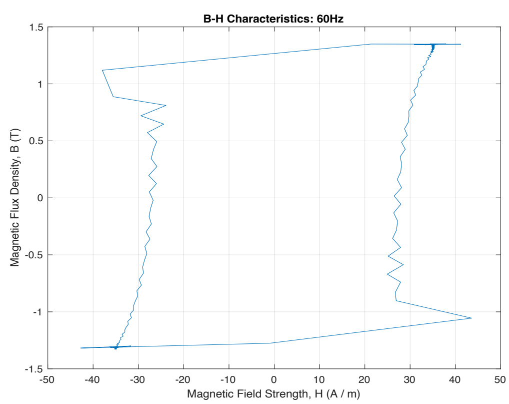
In this section, data is presented as each section indicates below.





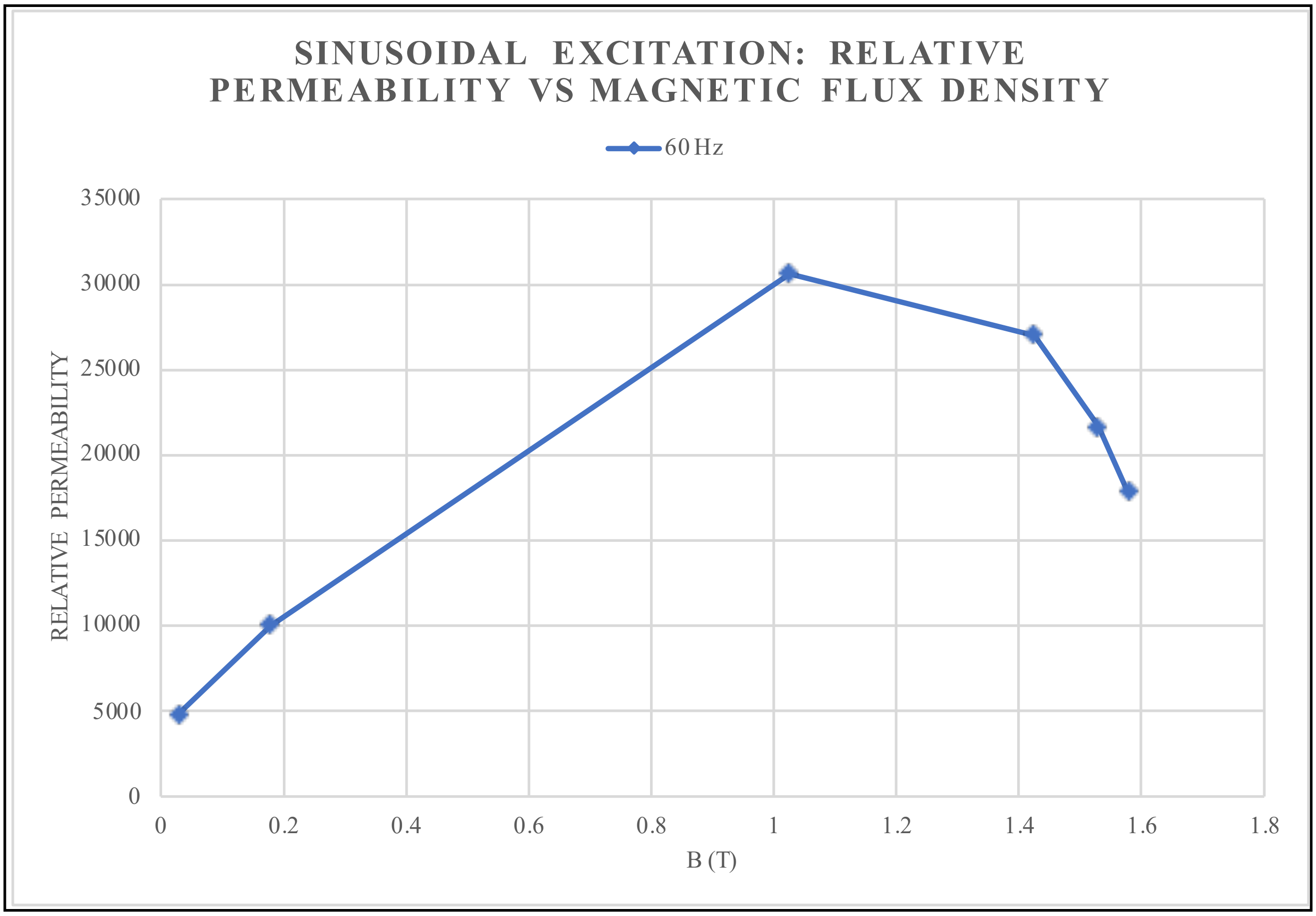
Sample Sinusoidal Excitation Waveform and B-H Plot. Sinusoidal Signal. 150.00 mV_{pp} 60Hz, Amplifier Gain X50.



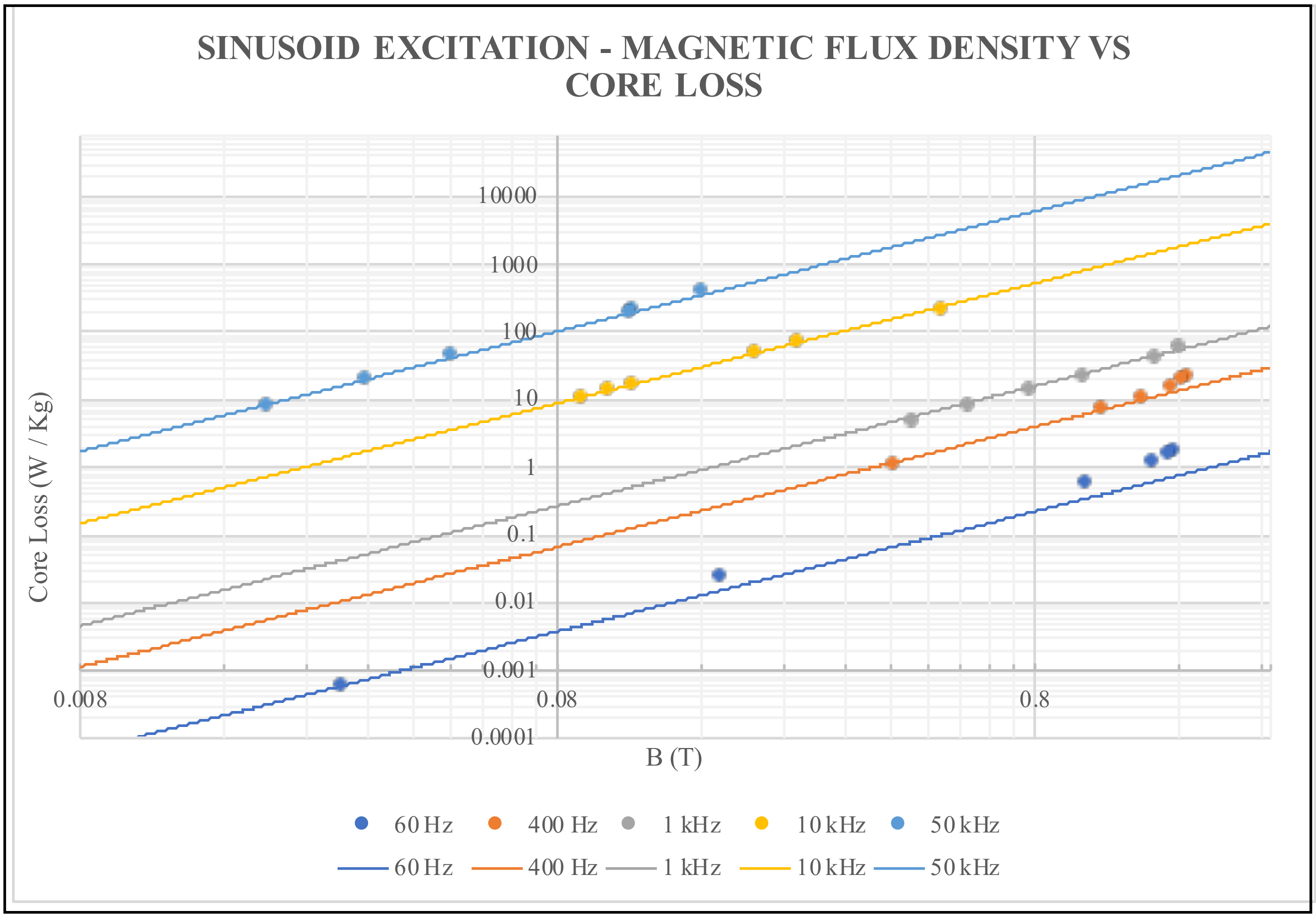


Sample Square Excitation Waveform and B-H Plot. Square Signal. 75.00 mV_{pp} 60Hz, Amplifier Gain X50.

a. Sinusoidal Excitation Magnetic Characterization.



60 Hz	
B (T)	**μ_r**
1.58	17851.3
1.53	21638.2
1.42	27071.1
1.02	30609.7
0.18	10082.2
0.03	4825.4

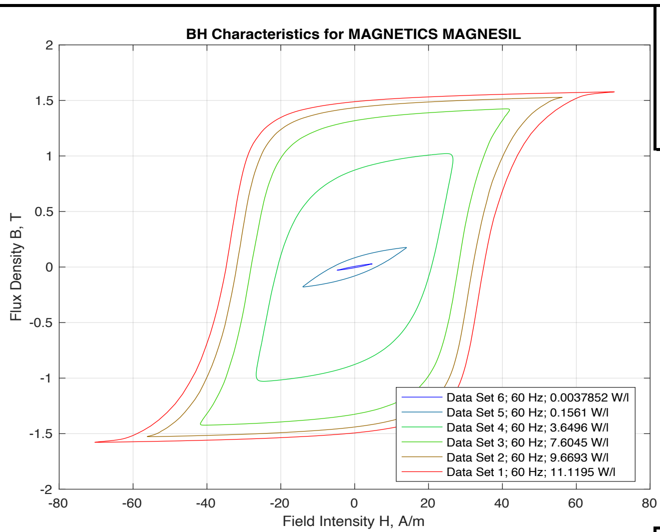


Magnetic Flux Density vs Core Loss - Table

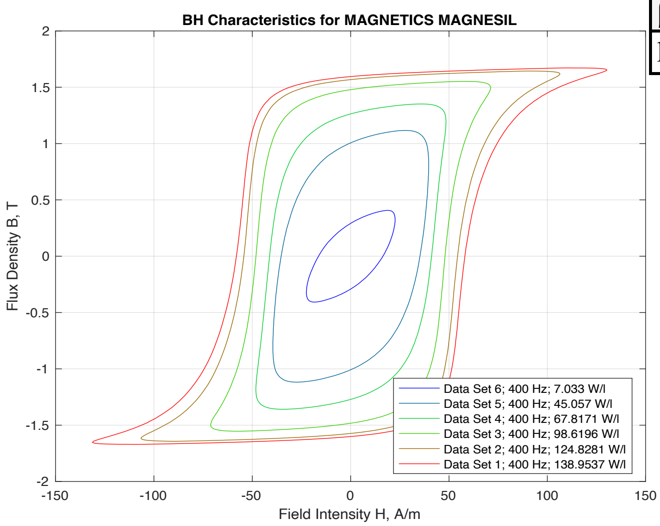
60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	**Core Loss (W/kg)**	**B (T)**	**Core Loss (W/kg)**	**B (T)**	**Core Loss (W/kg)**	**B (T)**	**Core Loss (W/kg)**
1.58	1.71	1.67	21.41	1.62	57.71	0.51	212.26
1.53	1.49	1.64	19.23	1.44	41.92	0.26	68.98
1.42	1.17	1.55	15.19	1.01	20.68	0.21	48.42
1.02	0.56	1.36	10.45	0.79	12.93	0.11	16.62
0.18	0.02	1.12	6.94	0.59	7.56	0.10	13.48
0.03	0.00	0.41	1.08	0.45	4.65	0.09	10.62

50 kHz	
B (T)	**Core Loss (W/kg)**
0.16	388.32
0.12	214.37
0.11	190.22
0.05	43.58
0.03	19.78
0.02	7.96

Empirical Model for Core Loss using Steinmetz Equation: Sinusoidal Excitation via Sudhoff Simulation



(a)



(b)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b}\right)^{\alpha} \left(\frac{B_{pk}}{B_b}\right)^{\beta}$$

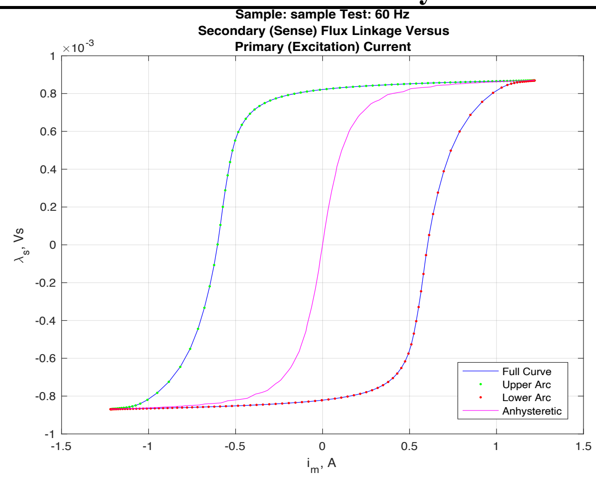
Steinmetz Coefficients for Curve Fit

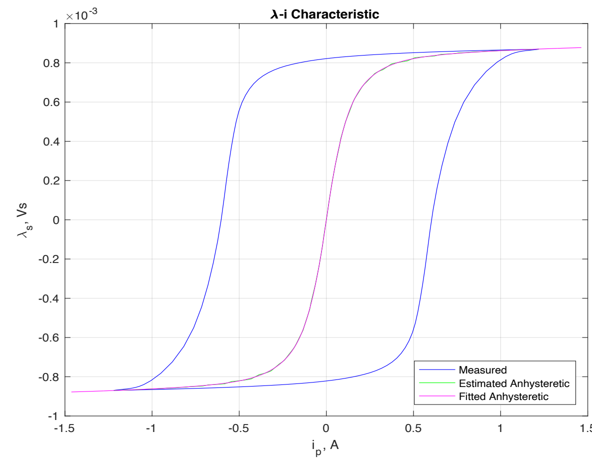
α	1.5195	
β	1.7735	
k_h	0.000657987	W / kg

Empirical Model Plot Sample – (a) 60 Hz. (b) 400 Hz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h, α, and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..

Anhysteric BH Plots: Sinusoidal Excitation





μ_r	α (1/T)	β (1/T)	γ (T)
153730.4484	0.42106	41.63478	1.7546
	0.0092424	3.444522	3.0338
f (Hz)	0.0072306	409.0416	1.819
60	0.0013276	22.59897	1.6207

$$B = \mu_B(B)H$$

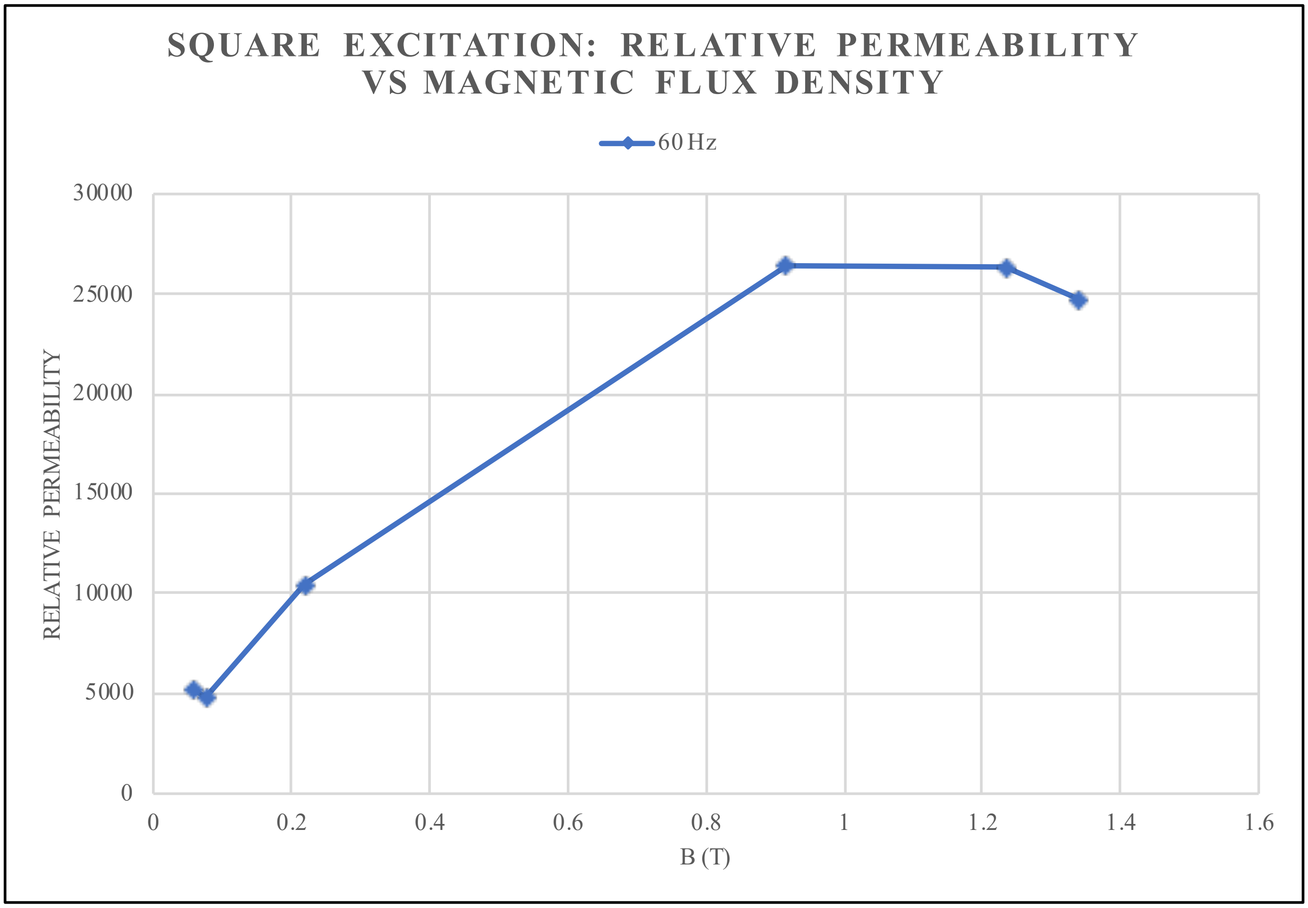
$$\mu_B(B) = \mu_B \frac{r(B)}{r(B) - 1}$$

$$r(B) = \frac{\mu_r}{\mu_r - 1} + \sum_{k=1}^{K} \alpha_k |B| + \delta_k \ln(\varepsilon_k + \zeta_k e^{-\beta_k |B|})$$

$$\delta_k = \frac{\alpha_k}{\beta_k} \qquad \zeta_k = \frac{1}{1+e^{-\beta_k \gamma_k}} \qquad \varepsilon_k = \frac{e^{-\beta_k \gamma_k}}{1+e^{-\beta_k \gamma_k}}$$

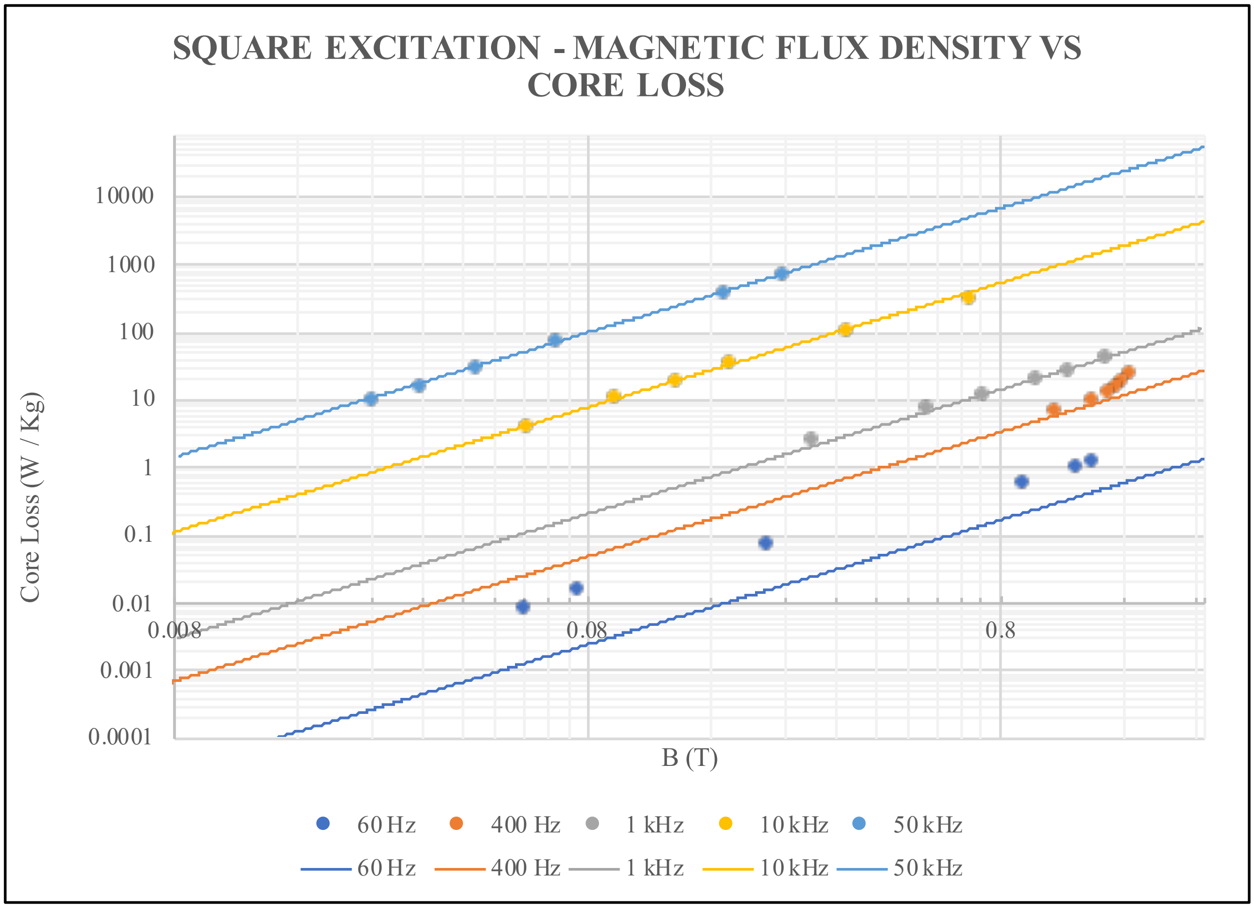
The anhysteric plot is computed by fitting the outer most BH curve within the plot, which coefficients are obtained as a function of flux density B from this equation. For more of the characteristic model equation shown above, see: G. M. Shane and S. D. Sudhoff, "Refinements in Anhysteretic Characterization and Permeability Modeling," in *IEEE Transactions on Magnetics*, vol. 46, no. 11, pp. 3834-3843, Nov. 2010.

b. Square Excitation Magnetic Characterization.



60 Hz

B (T)	μ_r
1.34	24690.55
1.23	26302.90
0.92	26410.68
0.22	10455.67
0.08	4817.73
0.06	5250.85

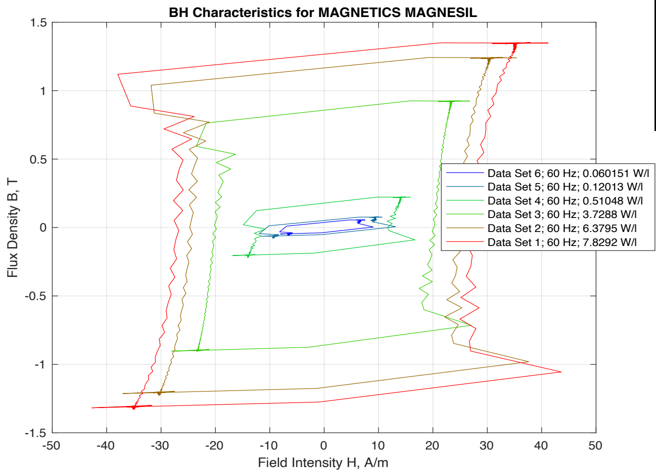


Magnetic Flux Density vs Core Loss - Table

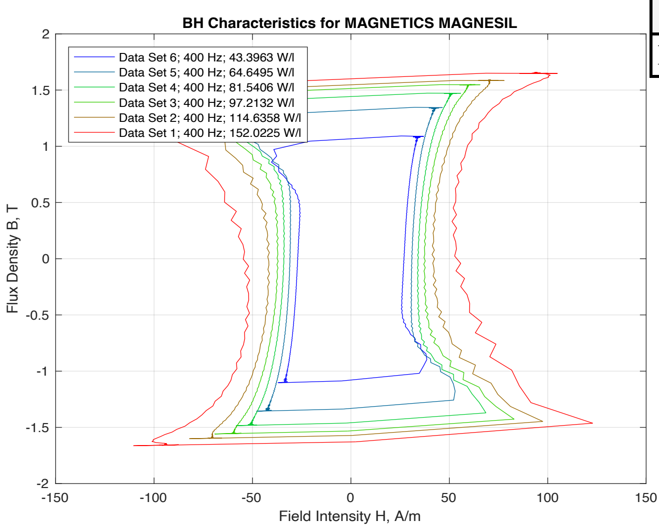
60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.34	1.16	1.66	22.92	1.46	39.55	0.68	308.35
1.23	0.95	1.60	17.38	1.18	26.39	0.34	100.57
0.92	0.55	1.55	14.78	0.98	18.95	0.18	32.26
0.22	0.07	1.48	12.43	0.73	11.54	0.13	18.62
0.08	0.02	1.35	9.87	0.53	6.93	0.09	10.04
0.06	0.01	1.10	6.63	0.28	2.46	0.06	3.95

50 kHz	
B (T)	Core Loss (W/kg)
0.24	643.05
0.17	369.92
0.07	67.84
0.04	29.09
0.03	15.54
0.02	9.24

Empirical Model for Core Loss using Steinmetz Equation: Square Excitation via Sudhoff Simulation



(a)



(b)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b}\right)^{\alpha} \left(\frac{B_{pk}}{B_b}\right)^{\beta}$$

Steinmetz Coefficients for Curve Fit

α	1.5756	
β	1.8368	
k_h	0.000403516	W / kg

Empirical Model Plot Sample – (a) 60 Hz. (b) 400 Hz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h, α, and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..

Section Two: Elevated Temperature Environmental Measurements. Magnetic Core Characterization Testing: Test Procedures and Results.

Purpose.
This test procedure is used to measure the B-H Curves, core losses, and permeability of the core under test at varying temperature.

Test Equipment.
The test equipment shall be used as follows:

Lab Asset No	Description	Manufacturer	Model No	Serial No
CHA0001	Environmental Chamber	Sun Systems	EC13W	AA1595
WAV0003	Arbitrary Waveform Generator	Keysight Technologies	EDU33212A	CN61310043
AMP0001	High Speed Power Amplifier	NF Electronic Instruments	4025	4025-112
OSC0003	Oscilloscope (500 MHz)	Keysight Technologies	MSOX4054A	MY61260112
PRO0003	10:1 200 MHz Differential Probe	Keysight Technologies	N2792A	PH61260009
PRO0009	Differential Probe	Rigol	RP1100D	20180742
PRO0005	AC / DC Current Probe	Keysight Technologies	1147B	JP61071359
CAP0001	5 uF Capacitor	Cornell Dubilier Electronics (CDE)	SCRN244R-F	None
CAP0002	5 uF Capacitor	Cornell Dubilier Electronics (CDE)	SCRN244R-F	None
RES0001	5 Ohm Resistor	Riedon	UB15-5RF1	None
LAB0001	Computer	AMPED	None	None

Test Procedures.

I. Core Loss Testing - Low Signal with Amplifier Setup – Room Temperature – Manual Procedure.

Per AMPED Standard AMP-STD-001, below is the procedure for manual operation of equipment for the Low Signal Setup, to be applied as follows. For a more detailed and general procedure to apply the test, refer to the referenced standard described here.

a. Turn on the measurement equipment and allow sufficient time for stabilization (e.g. 20 minutes).

b. Set the Arbitrary Waveform Generator to the following settings.

- Begin with a low signal.
  - Frequency. Set frequency as initial starting point at 60 Hz. Increment based on the desired frequencies necessary to perform measurements.
  - Amplitude. Begin with an amplitude value, in terms of peak-to-peak (V_{PP}), at 10 milli. Increase where deemed appropriate to make sure a fully functioning signal is observed in an acceptable tolerance.

c. Set the Power Amplifier values.

- Be sure to press input cable connected to on (usually A).
- Press the desired gain. Performed in these tests at “X50”.

d. Set the Oscilloscope to the following settings.

- Specify Probe Attenuation.
    - Measurements were performed with a Keysight 1147B Current Probe has a fixed attenuation ratio of 0.1 V/A and cannot be changed.
    - Voltage Probe from Keysight, the N2792, was used for measurements, and has fixed attenuation ratio of 5:1 after calibration with oscilloscope. Probe with Asset Number PRO0003 was used to acquire data from 60 Hz – 1 kHz.
    - Voltage Probe from Rigol, the RP1100D, was used for measurements 10 - 50 kHz, and has fixed attenuation ratio of 200:1 after calibration.
    - All data was captured with High Resolution Settings under Waveform-Acquire Menu.

e. Turn output of Arbitrary Waveform Generator on.

f. Level the output voltage at the offset adjust with flat head screw driver, if possible. Note if probe does not have that capability.

- For data presented, Voltage probe with asset number PRO0009 does not have the capability.

g. Examine the Waveform on the Oscilloscope read from the Current Probe on the input side and the Differential Probe on the Output Side.

- Be sure to capture 3 - 5 periods of the excitation signal being applied.
- Look for point of saturation for the core. This can be visually examined when the waveform's maximum value no longer increases. Sine and Ramp waveforms flatten, Square becomes more in a curve. See Data Presentation for examples.
- Magnetic Flux Density is optional for oscilloscope waveforms but recommended.

h. Auto zero and Degauss the Current Probe before step i. Also Degauss where Average Current Waveform value climbs above an acceptable tolerance of +/- 10 mA.

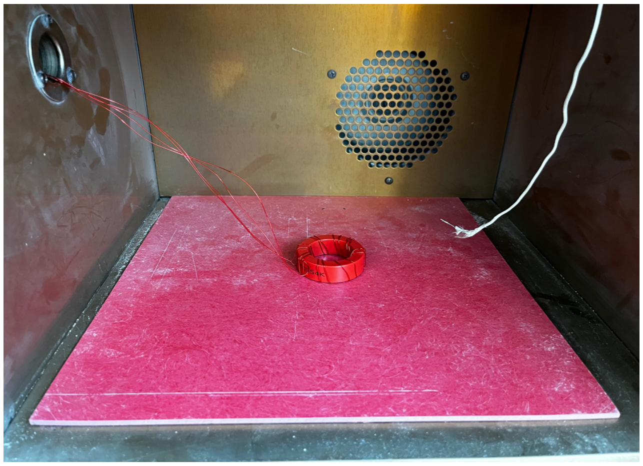
i. Setup included correction components for DC Biasing part of the setup. See the test setup section for a diagram. Note a 5 Ohm Resistor was in series with two 5 µF Capacitors in parallel.

j. Repeat steps a - f for Square Waveform, Ramp Waveform, or other excitation waveforms for examined interest.

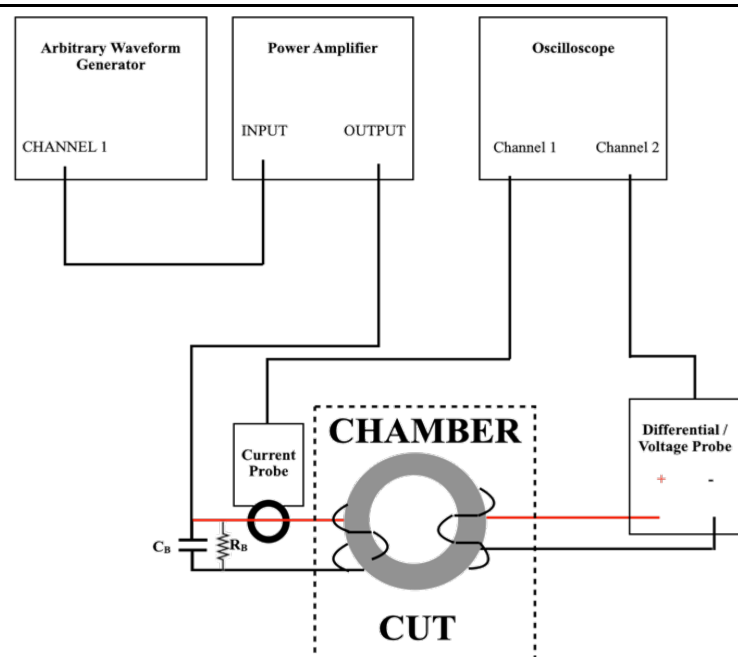
k. Record relevant data for Data Presentation.

Setup.

Core Testing. Configure the test equipment as shown below, with one figure showing the actual test setup, and another as the block diagram.



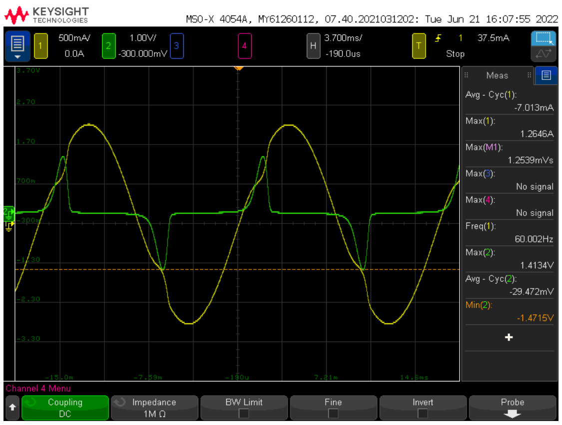
Core Loss Testing - Low Voltage with Amplifier. Typical Test Setup.

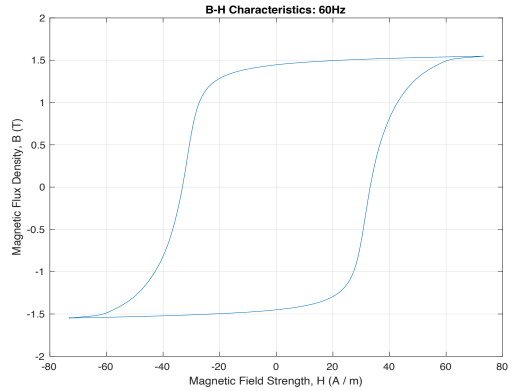


Core Loss Testing - Low Voltage with Amplifier. Typical Test Setup: System Block Diagram.

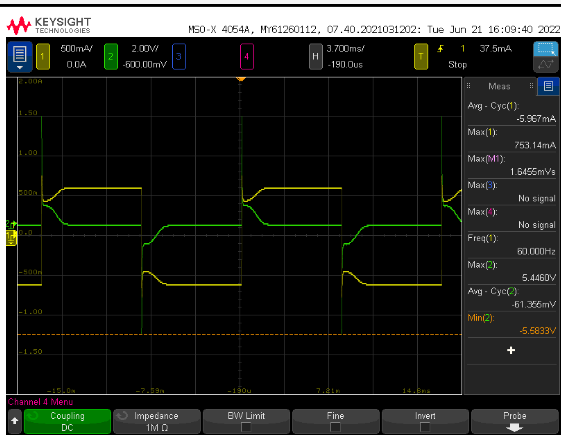
Data Presentation.

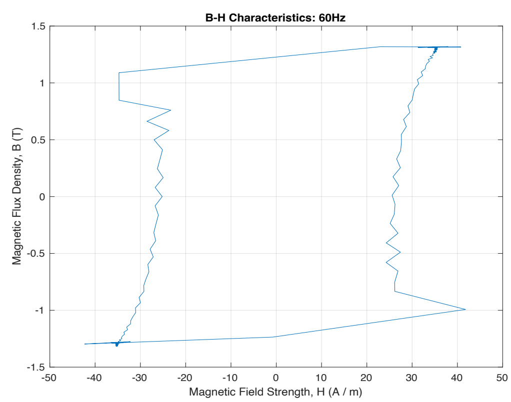
In this section, data is presented as each section indicates below.





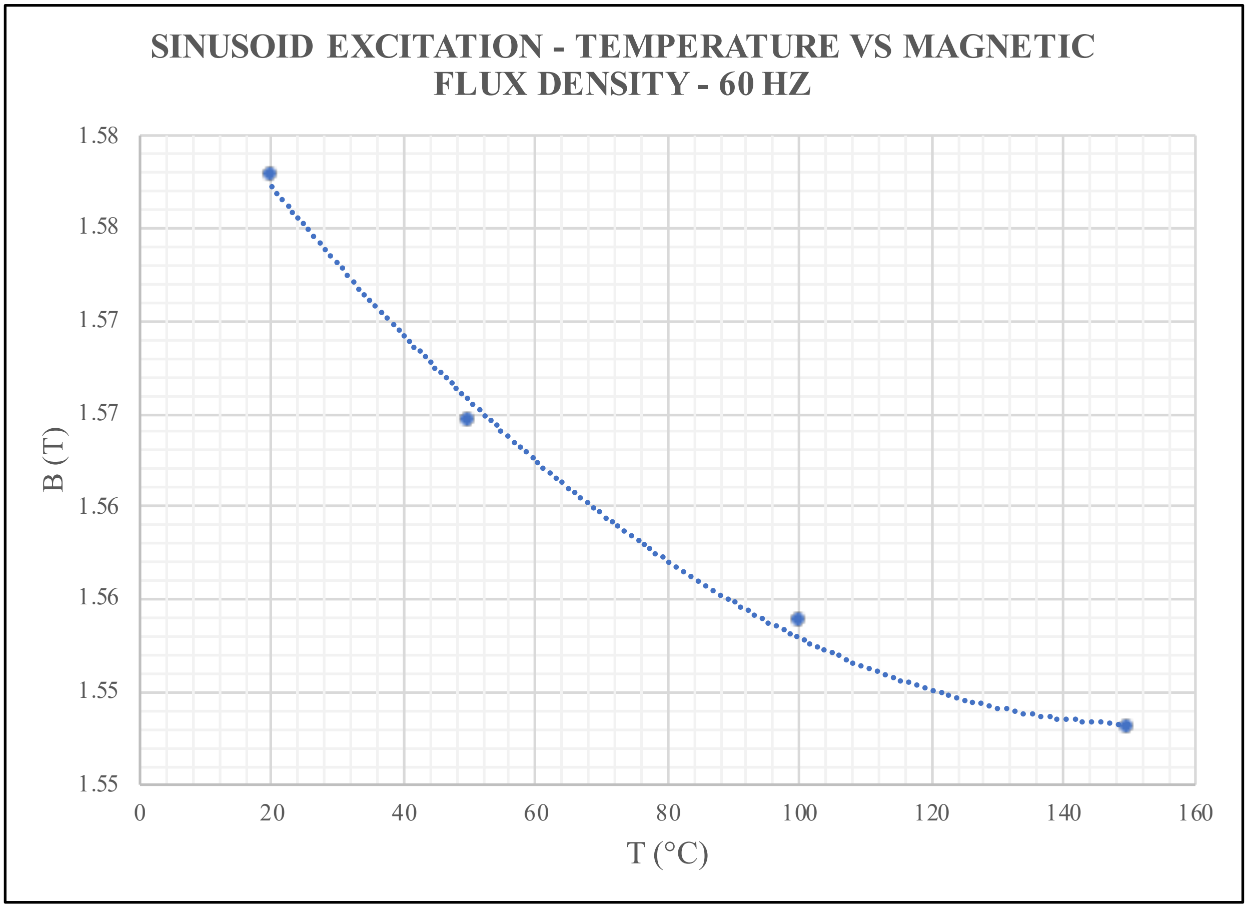
Sample Sinusoidal Excitation Waveform and B-H Plot. Sinusoidal Signal. 156.00 mV$_{pp}$ 60Hz, Amplifier Gain X50. 150°C.





Sample Square Excitation Waveform and B-H Plot. Square Signal. 75.00 mV$_{pp}$ 60 Hz, Amplifier Gain X50. 150°C.

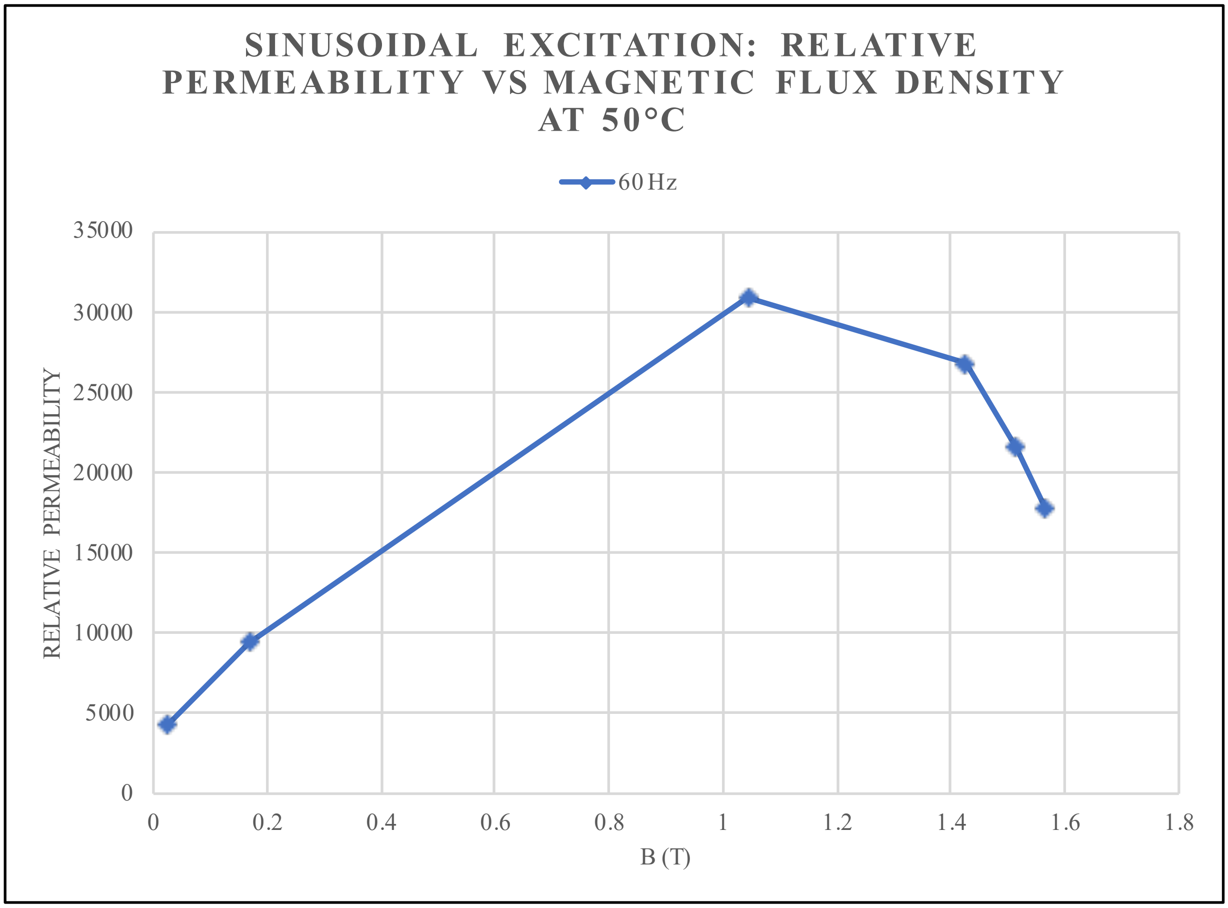
d. Sinusoidal Excitation Magnetic Characterization.



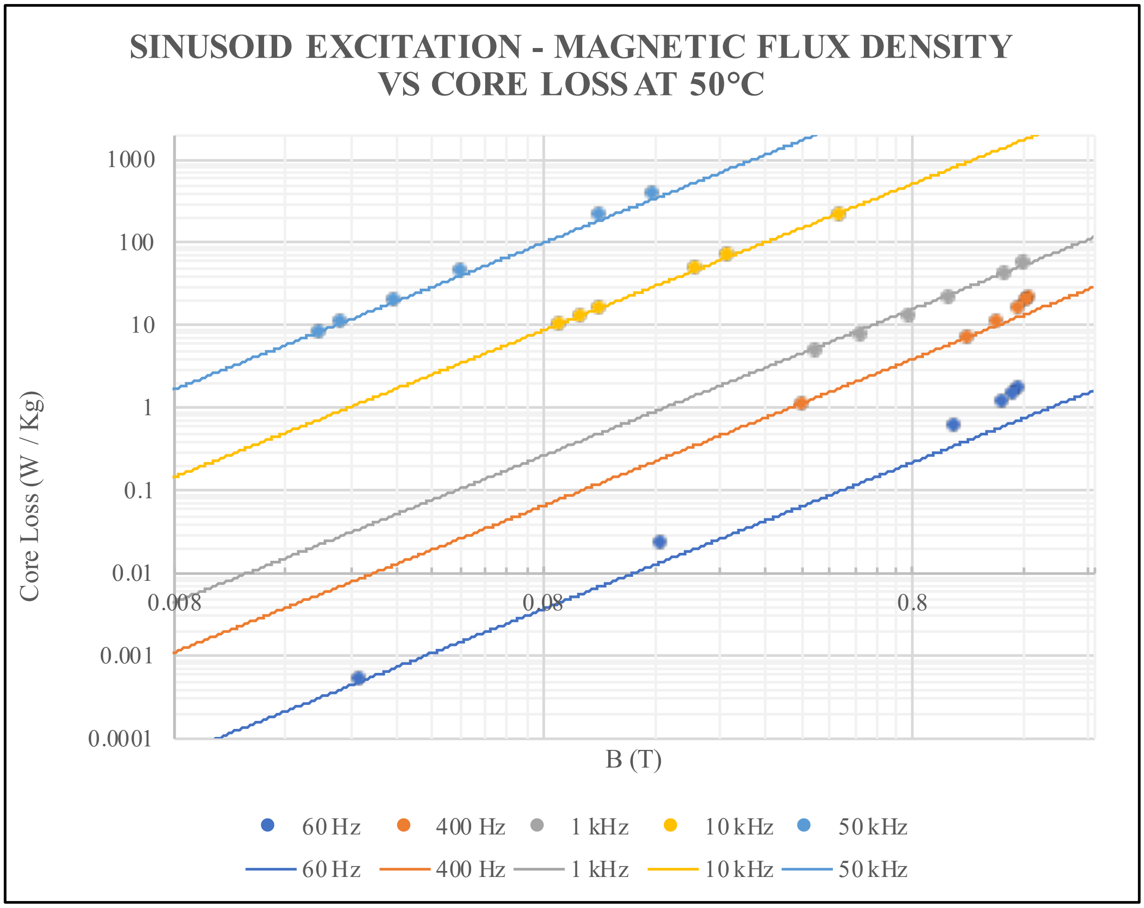
Temperature Dependence vs Core Loss - Table

60 Hz		400 Hz		1 kHz		10 kHz	
T (°C)	**B (T)**	**T (°C)**	**B (T)**	**T (°C)**	**B (T)**	**T (°C)**	**B (T)**
20.00	1.58	20.00	1.67	20.00	1.62	20.00	0.51
50.00	1.56	50.00	1.67	50.00	1.61	50.00	0.52
100.00	1.55	100.00	1.65	100.00	1.61	100.00	0.52
150.00	1.55	150.00	1.64	150.00	1.61	150.00	0.52

50 kHz	
T (°C)	**B (T)**
20.00	0.16
50.00	0.16
100.00	0.16
150.00	0.16



60 Hz	
B (T)	**μ_r**
1.56	17803.96
1.51	21607.01
1.42	26833.96
1.04	30935.49
0.17	9452.94
0.03	4317.78

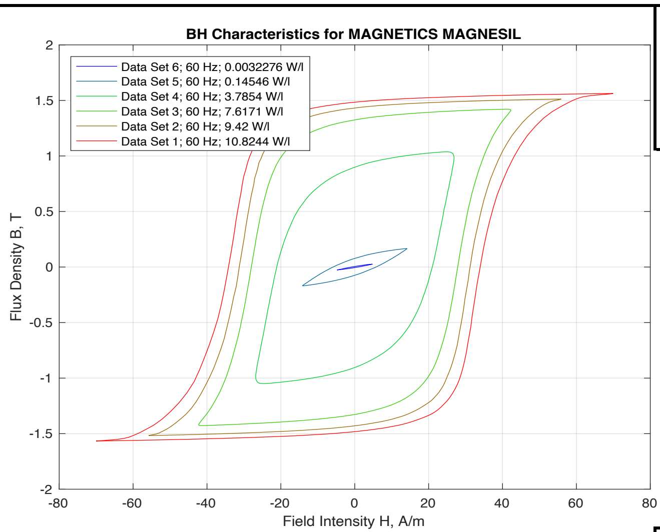


Magnetic Flux Density vs Core Loss - Table

60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	**Core Loss (W/kg)**	**B (T)**	**Core Loss (W/kg)**	**B (T)**	**Core Loss (W/kg)**	**B (T)**	**Core Loss (W/kg)**
1.56	1.67	1.67	21.02	1.61	55.04	0.52	212.93
1.51	1.45	1.64	18.91	1.45	41.22	0.25	66.22
1.42	1.17	1.56	14.96	1.01	20.28	0.21	46.22
1.04	0.58	1.37	10.48	0.79	12.85	0.11	15.55
0.17	0.02	1.14	7.02	0.58	7.49	0.10	12.58
0.03	0.00	0.40	1.06	0.44	4.58	0.09	9.89

50 kHz	
B (T)	**Core Loss (W/kg)**
0.52	212.93
0.25	66.22
0.21	46.22
0.11	15.55
0.10	12.58
0.09	9.89

Empirical Model for Core Loss using Steinmetz Equation: Sinusoidal Excitation via Sudhoff Simulation



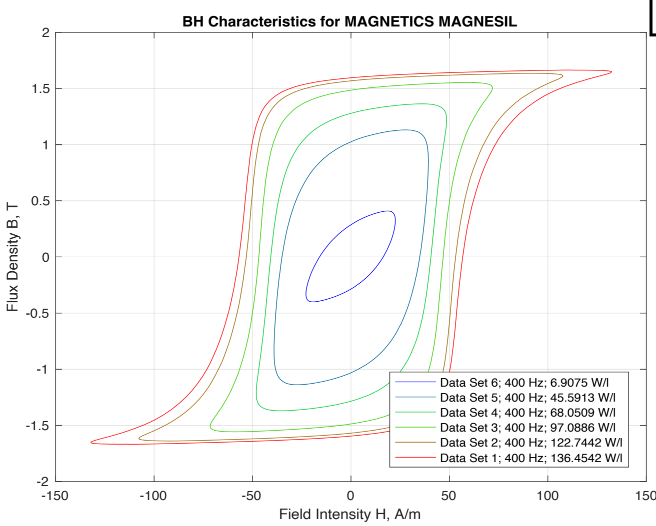
(a)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b}\right)^{\alpha} \left(\frac{B_{pk}}{B_b}\right)^{\beta}$$

Steinmetz Coefficients for Curve Fit 50°C

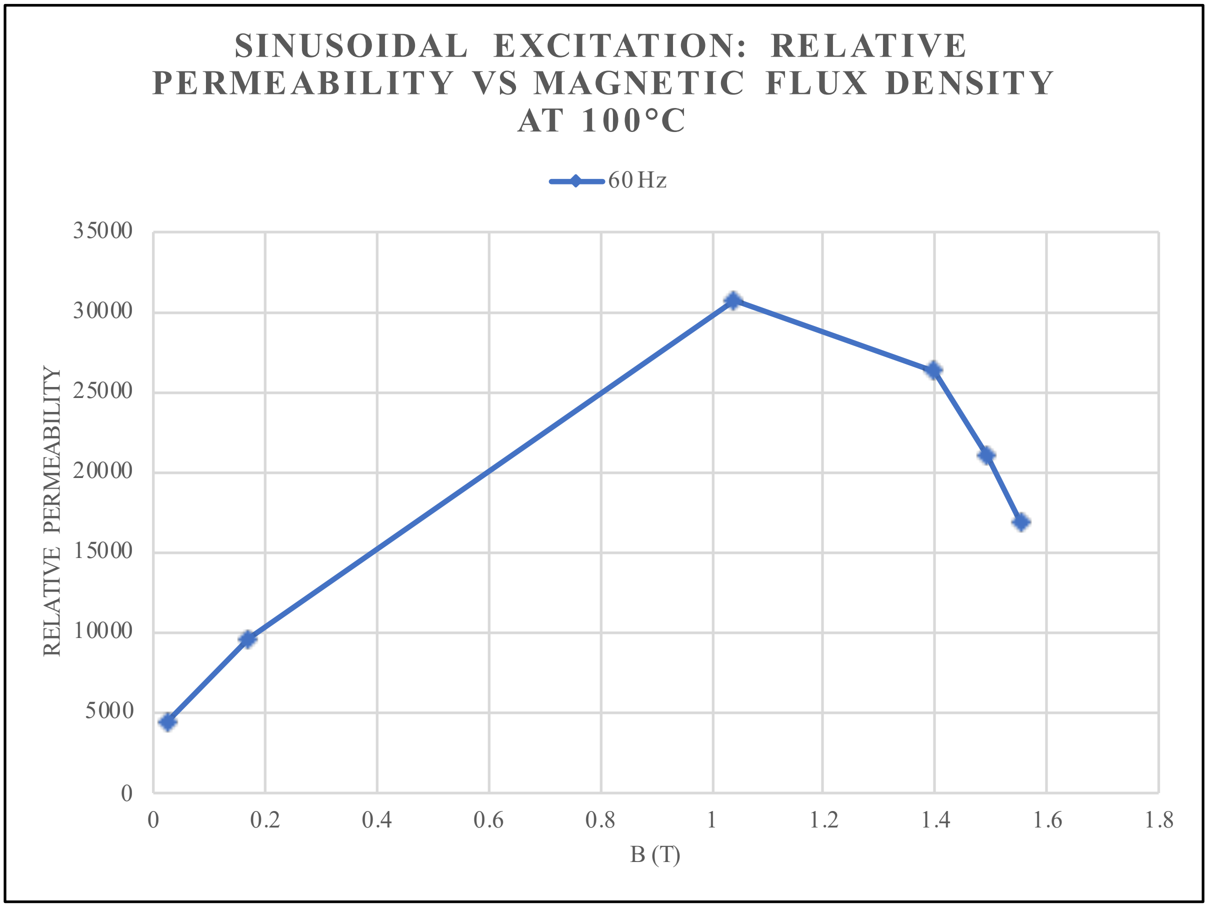
α	1.5172	
β	1.7724	
k_h	0.00065641	W / kg



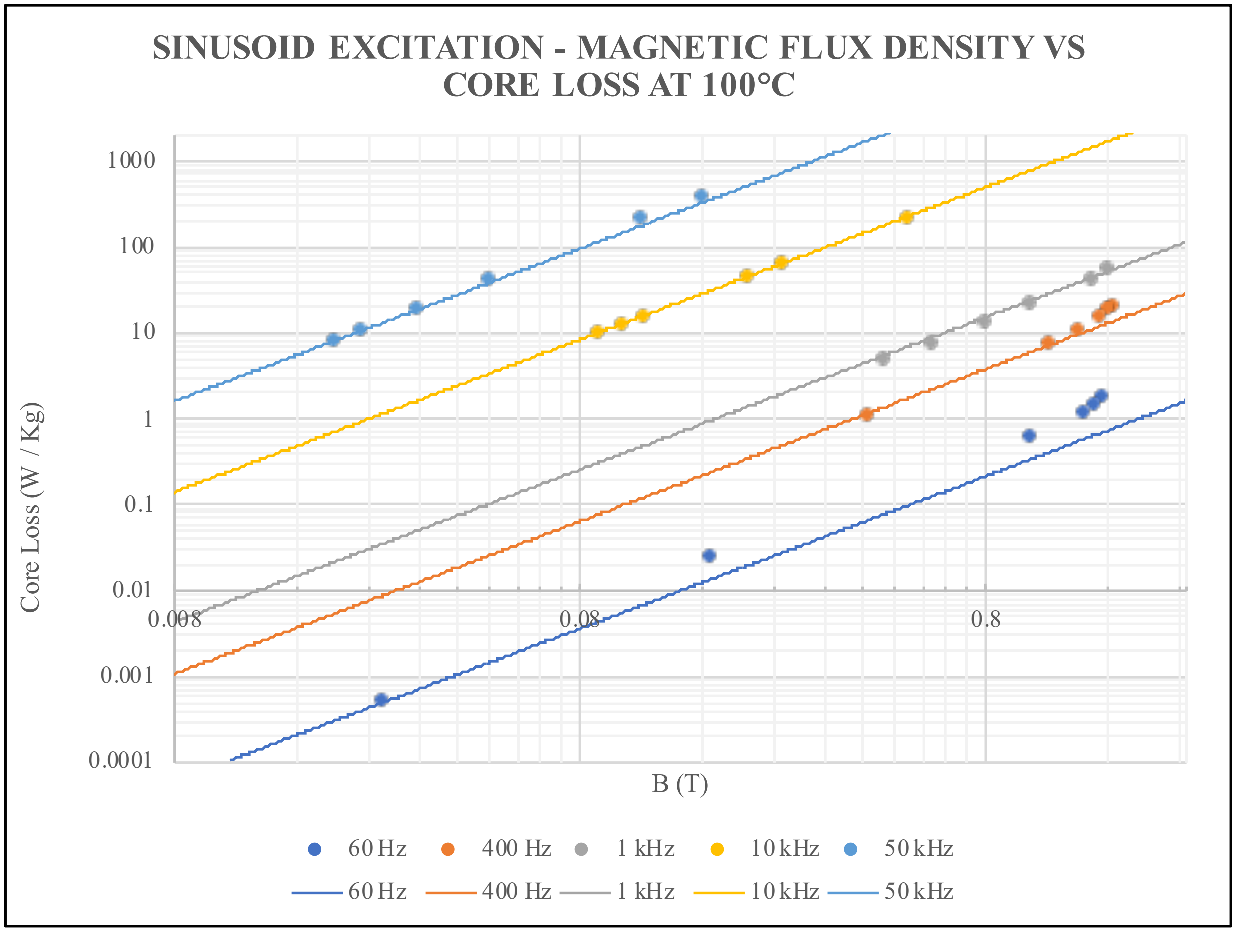
(b)

Empirical Model Plot Sample – (a) 60 Hz. (b) 400 Hz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h, α, and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..



60 Hz	
B (T)	**μ_r**
1.55	16855.38
1.49	21052.19
1.40	26316.29
1.04	30731.95
0.17	9648.05
0.03	4498.83

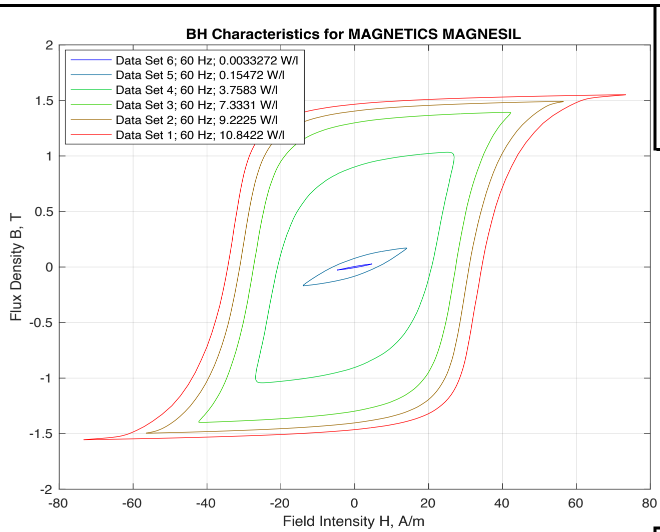


Magnetic Flux Density vs Core Loss - Table

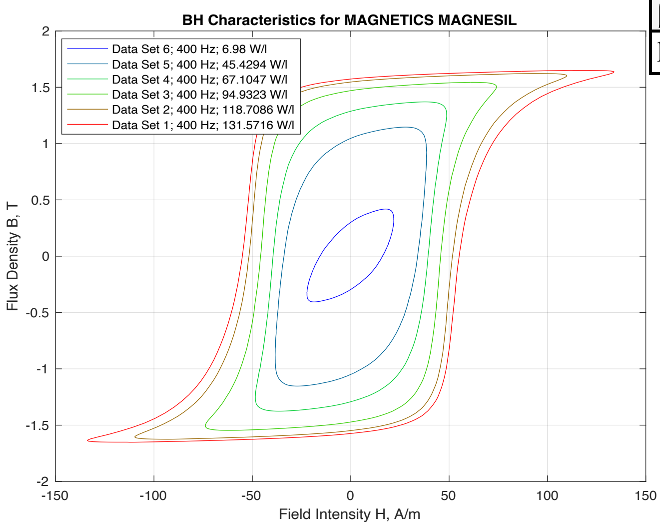
60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.55	1.67	1.65	20.27	1.61	54.27	0.52	205.52
1.49	1.42	1.62	18.29	1.46	40.97	0.26	63.66
1.40	1.13	1.55	14.63	1.03	20.36	0.21	44.37
1.04	0.58	1.37	10.34	0.80	12.71	0.11	15.02
0.17	0.02	1.15	7.00	0.59	7.41	0.10	12.13
0.03	0.00	0.41	1.08	0.45	4.55	0.09	9.50

50 kHz	
B (T)	Core Loss (W/kg)
0.16	367.55
0.11	203.98
0.05	41.21
0.03	18.61
0.02	10.02
0.02	7.57

Empirical Model for Core Loss using Steinmetz Equation: Sinusoidal Excitation via Sudhoff Simulation



(a)



(b)

Steinmetz Equation

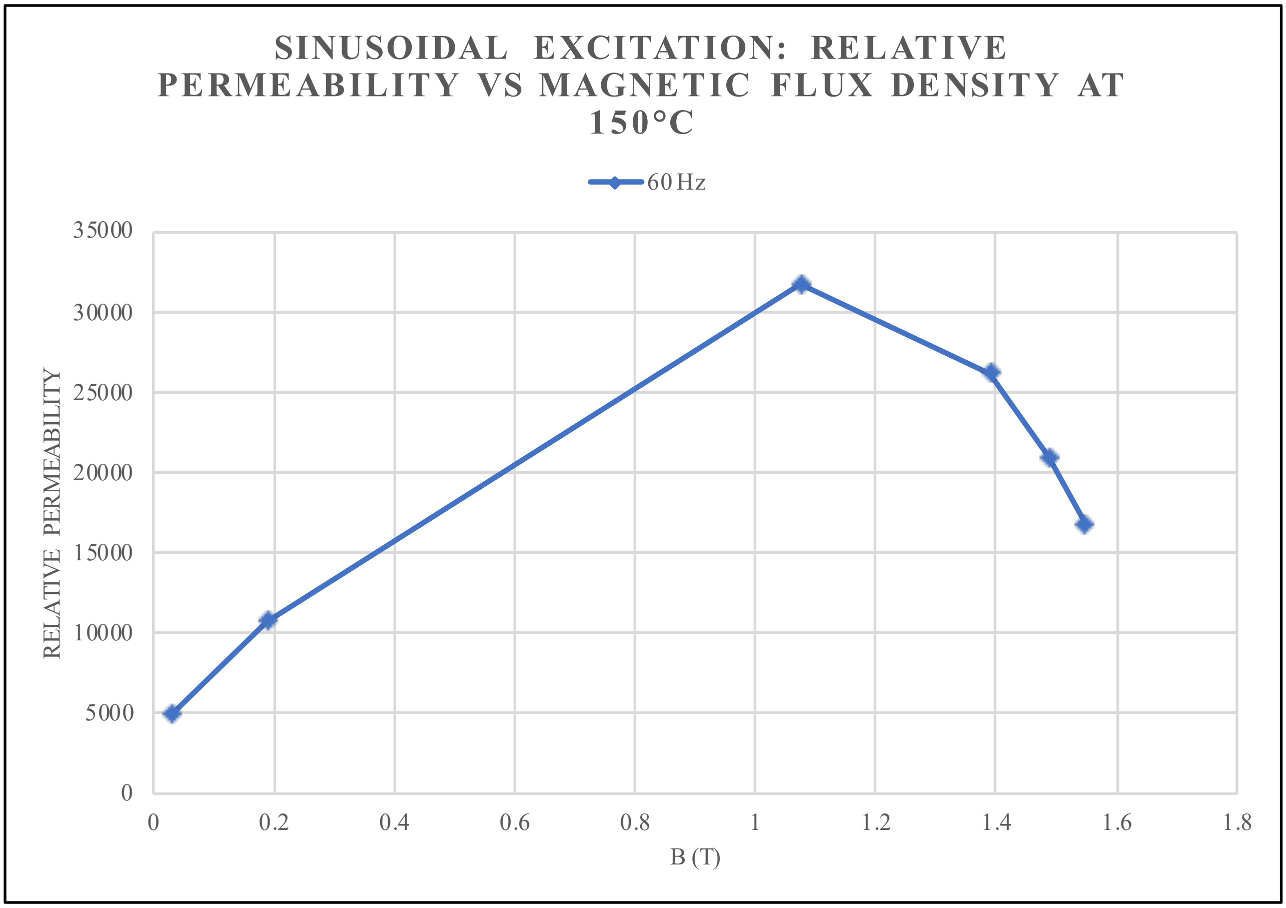
$$p_w = k_h \left(\frac{f}{f_b}\right)^{\alpha} \left(\frac{B_{pk}}{B_b}\right)^{\beta}$$

Steinmetz Coefficients for Curve Fit 100°C

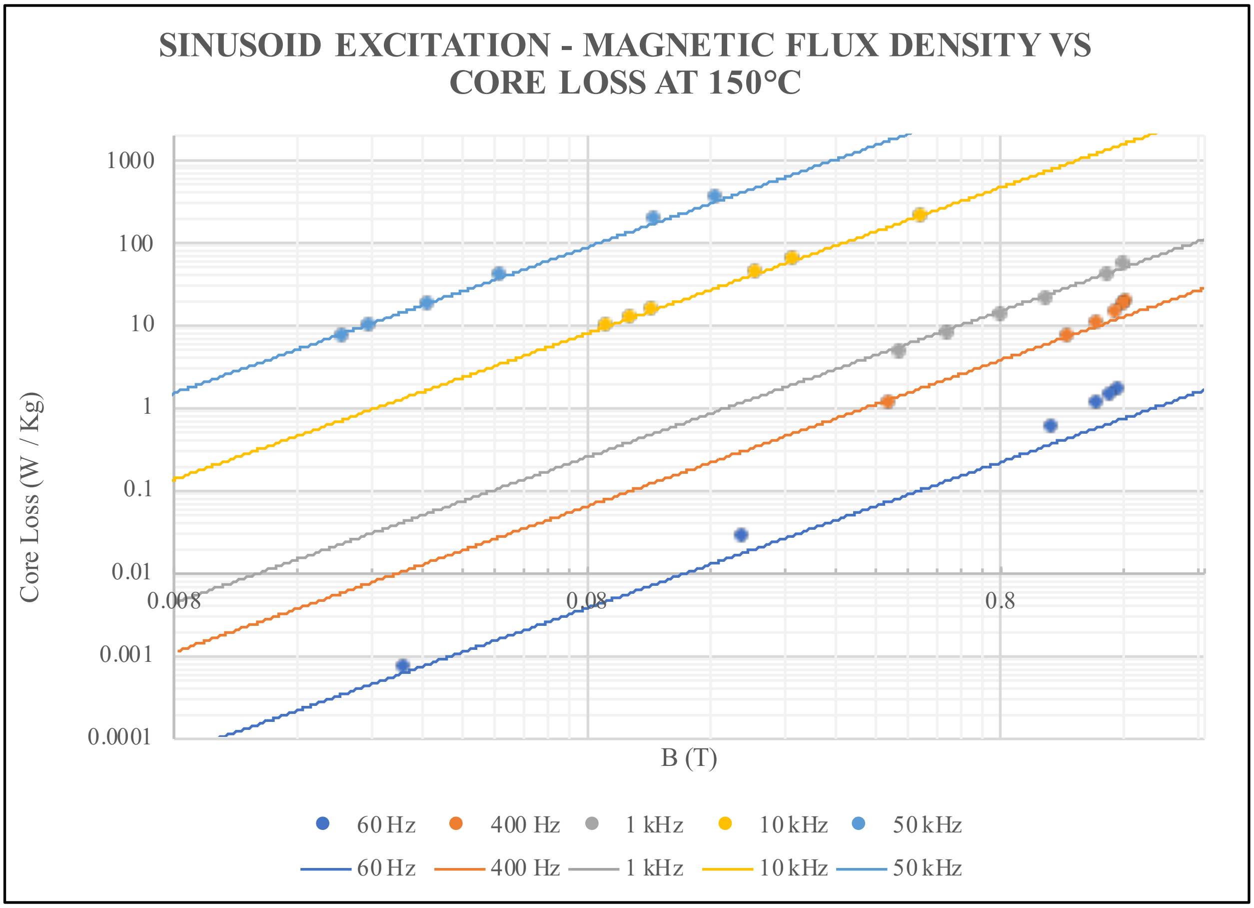
α	1.5137	
β	1.7729	
k_h	0.000651761	W / kg

Empirical Model Plot Sample – (a) 60 Hz. (b) 10 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h, α, and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..



60 Hz	
B (T)	**μ_r**
1.55	16820.81
1.49	21004.33
1.39	26268.30
1.08	31770.34
0.19	10773.58
0.03	4898.77

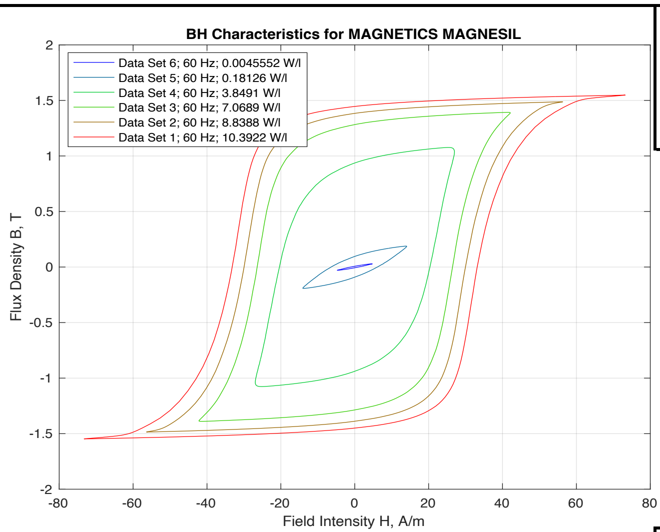


Magnetic Flux Density vs Core Loss - Table

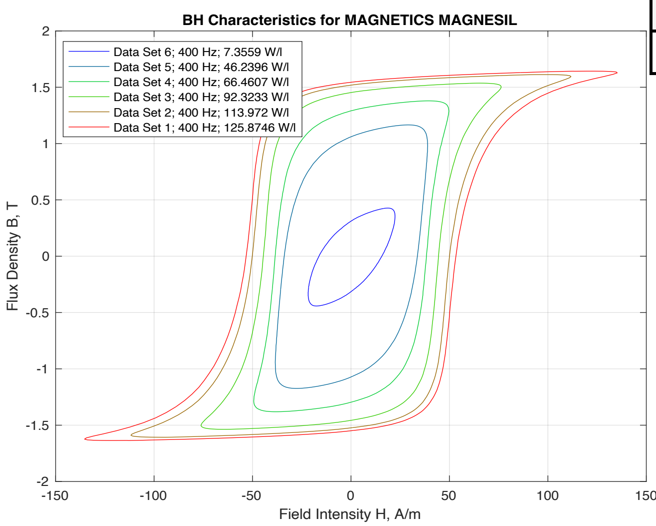
60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.55	1.60	1.64	19.40	1.61	53.83	0.52	205.52
1.49	1.36	1.61	17.56	1.46	40.88	0.26	63.66
1.39	1.09	1.54	14.22	1.04	20.46	0.21	44.37
1.08	0.59	1.38	10.24	0.81	12.99	0.11	15.02
0.19	0.03	1.17	7.12	0.60	7.63	0.10	12.13
0.03	0.00	0.43	1.13	0.46	4.68	0.09	9.50

50 kHz	
B (T)	Core Loss (W/kg)
0.16	346.20
0.12	190.73
0.05	38.42
0.03	17.70
0.02	9.42
0.02	7.15

Empirical Model for Core Loss using Steinmetz Equation: Sinusoidal Excitation via Sudhoff Simulation



(a)



(b)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b}\right)^{\alpha} \left(\frac{B_{pk}}{B_b}\right)^{\beta}$$

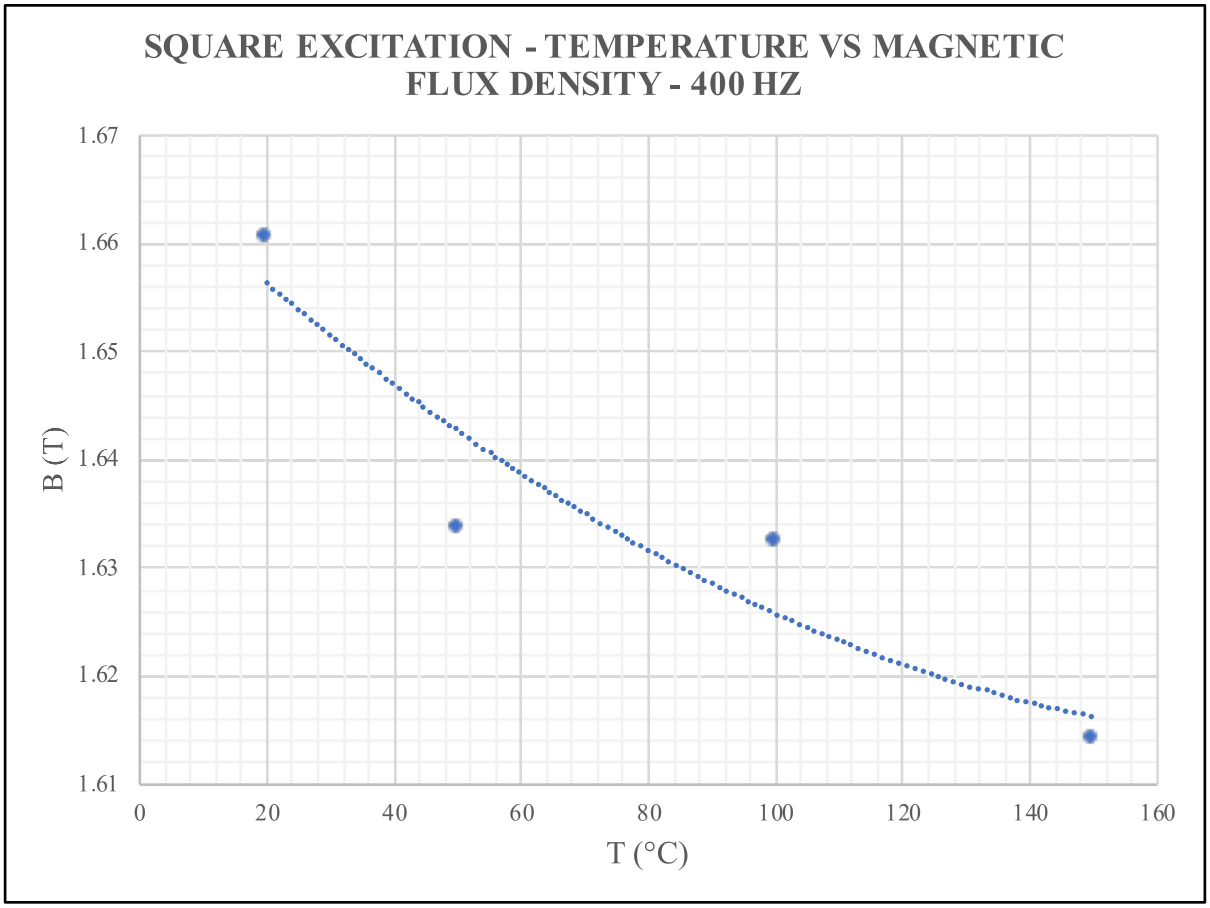
Steinmetz Coefficients for Curve Fit 150°C

α	1.4953	
β	1.7662	
k_h	0.000726712	W / kg

Empirical Model Plot Sample – (a) 60 Hz. (b) 400 Hz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h, α, and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..

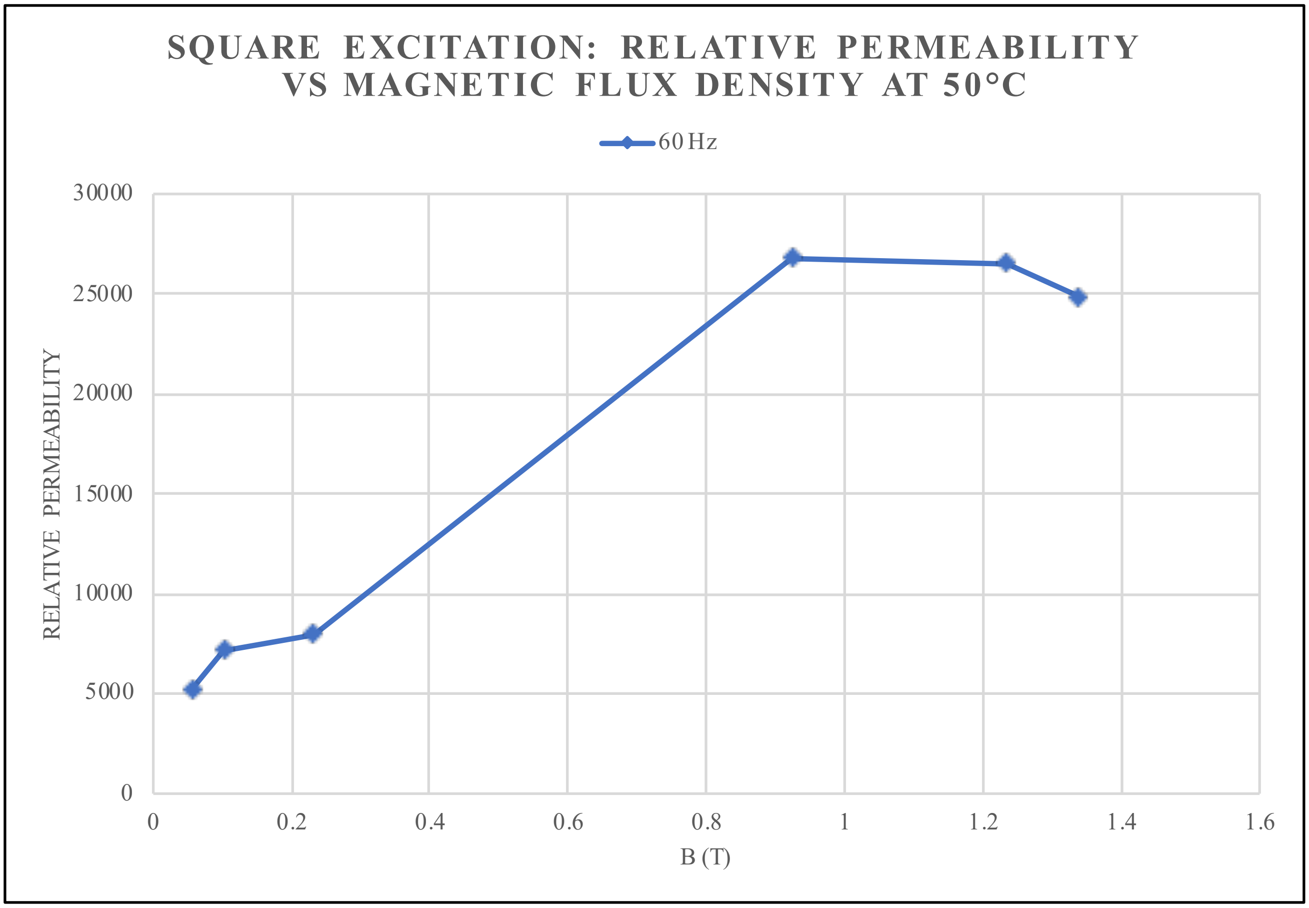
e. Square Excitation Magnetic Characterization.



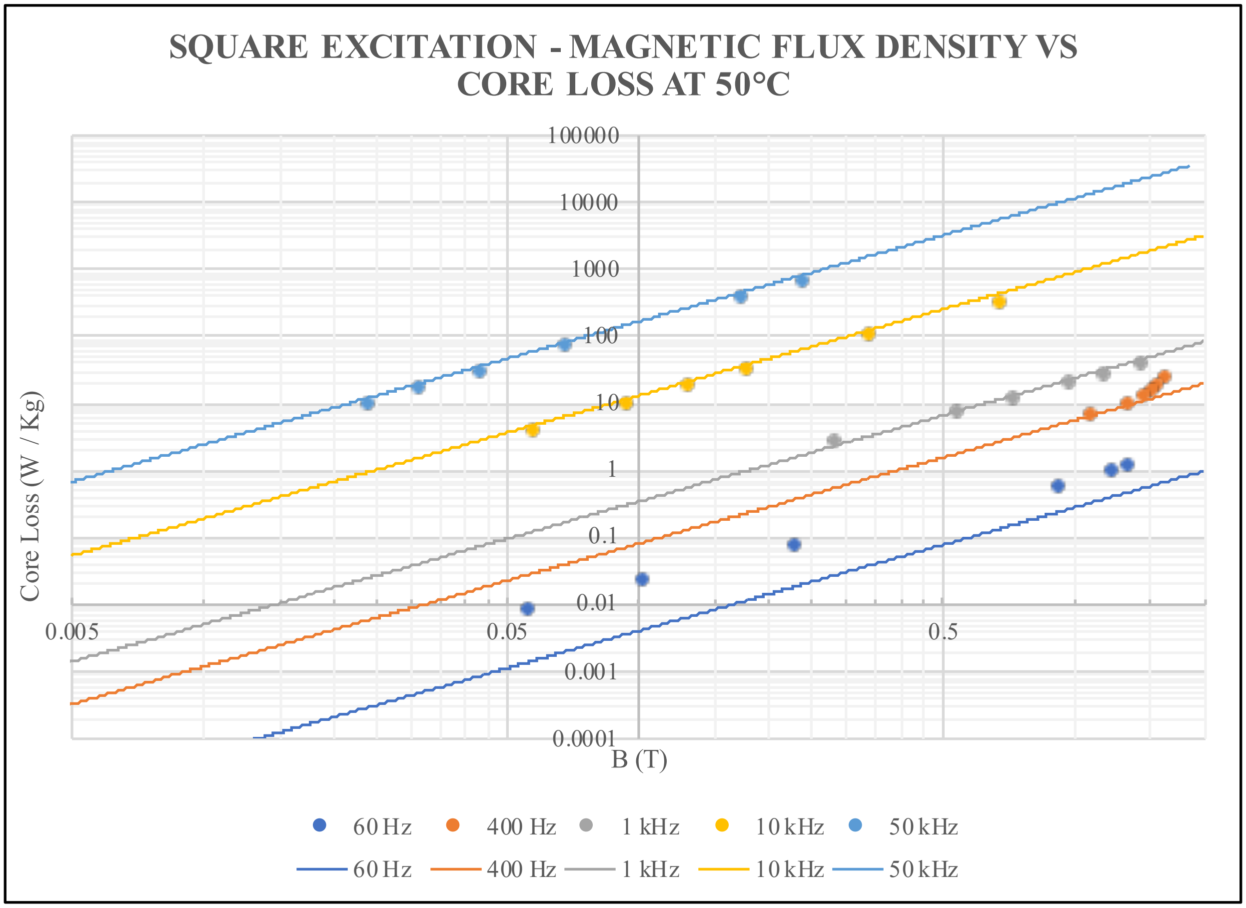
Temperature Dependence vs Core Loss - Table

60 Hz		400 Hz		1 kHz		10 kHz	
T (°C)	B (T)	T (°C)	B (T)	T (°C)	B (T)	T (°C)	B (T)
20.00	1.34	20.00	1.66	20.00	1.46	20.00	0.68
50.00	1.34	50.00	1.63	50.00	1.44	50.00	0.68
100.00	1.31	100.00	1.63	100.00	1.46	100.00	0.69
150.00	1.32	150.00	1.61	150.00	1.46	150.00	0.69

50 kHz	
T (°C)	B (T)
20.00	0.24
50.00	0.24
100.00	0.24
150.00	0.24



60 Hz	
B (T)	**μ_r**
1.34	24867.37
1.23	26504.07
0.92	26767.85
0.23	7957.75
0.10	7170.57
0.06	5238.47

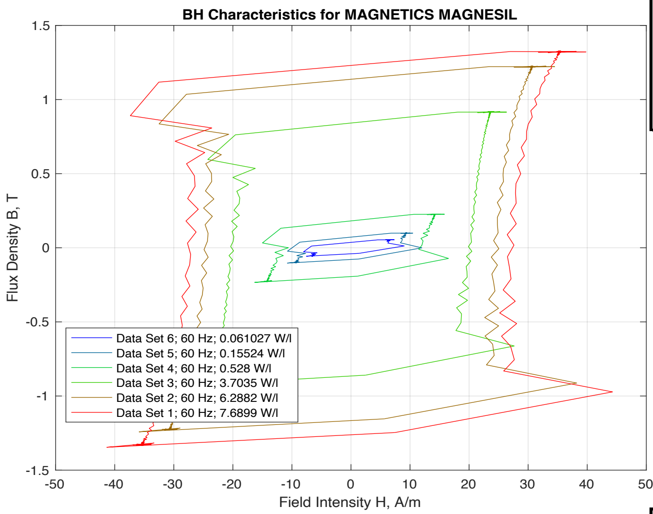


Magnetic Flux Density vs Core Loss - Table

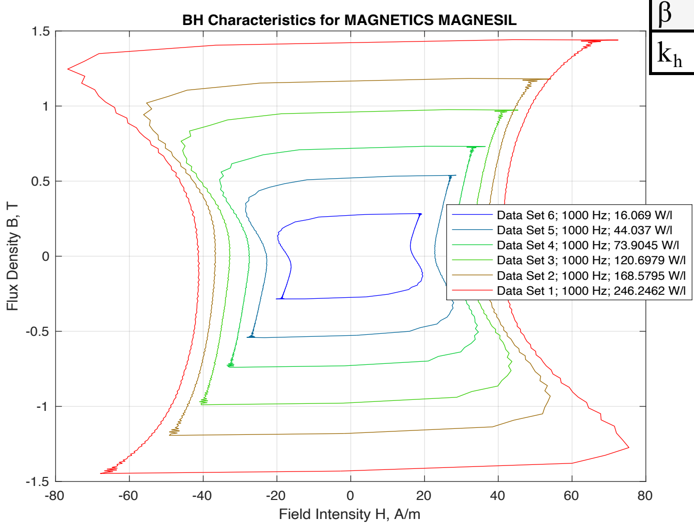
60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	**Core Loss (W/kg)**	**B (T)**	**Core Loss (W/kg)**	**B (T)**	**Core Loss (W/kg)**	**B (T)**	**Core Loss (W/kg)**
1.34	1.14	1.63	22.29	1.44	37.75	0.68	300.82
1.23	0.93	1.57	16.90	1.19	25.85	0.34	96.59
0.92	0.55	1.53	14.33	0.98	18.51	0.18	30.70
0.23	0.07	1.46	12.00	0.74	11.34	0.13	17.61
0.10	0.02	1.34	9.56	0.54	6.76	0.09	9.46
0.06	0.01	1.10	6.57	0.28	2.46	0.06	3.71

50 kHz	
B (T)	**Core Loss (W/kg)**
0.24	636.53
0.17	366.03
0.07	67.05
0.04	28.81
0.03	15.42
0.02	9.17

Empirical Model for Core Loss using Steinmetz Equation: Square Excitation via Sudhoff Simulation



(a)



(b)

Steinmetz Equation

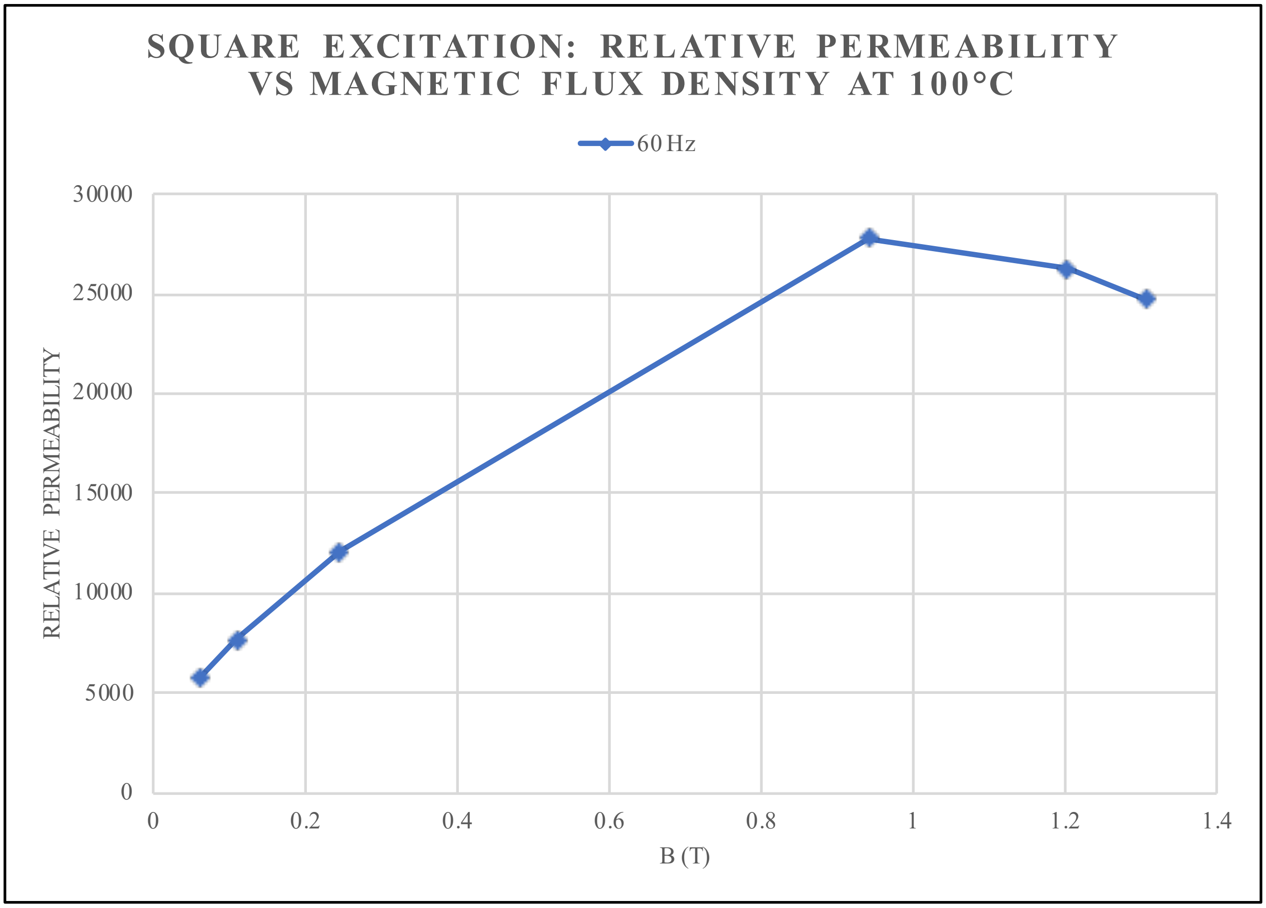
$$p_w = k_h \left(\frac{f}{f_b}\right)^{\alpha} \left(\frac{B_{pk}}{B_b}\right)^{\beta}$$

Steinmetz Coefficients for Curve Fit 50°C

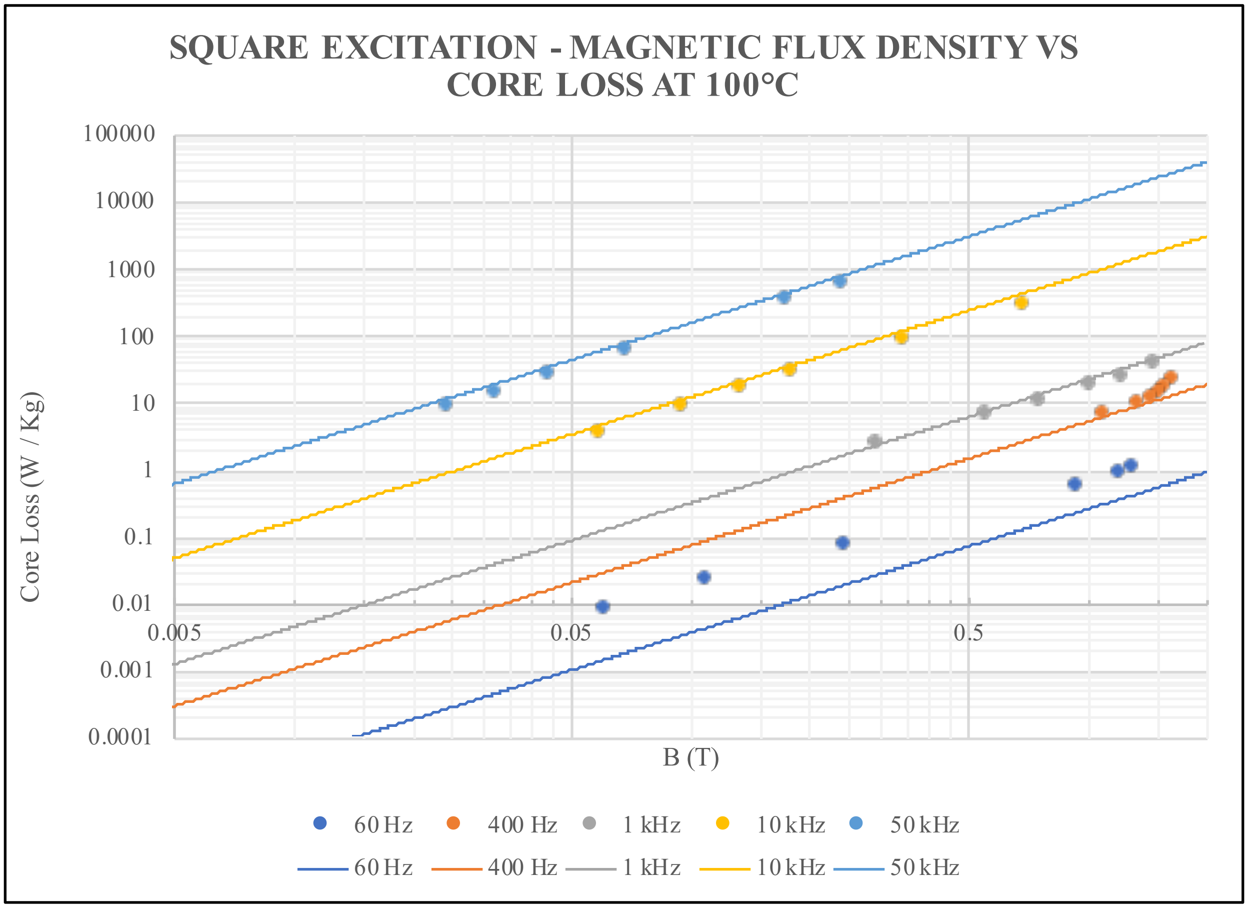
α	1.5806	
β	1.8384	
k_h	0.000434698	W / kg

Empirical Model Plot Sample – (a) 60 Hz. (b) 1 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h, α, and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..



60 Hz	
B (T)	**μ_r**
1.31	24705.09
1.20	26256.58
0.94	27744.58
0.25	12119.54
0.11	7721.63
0.06	5765.97

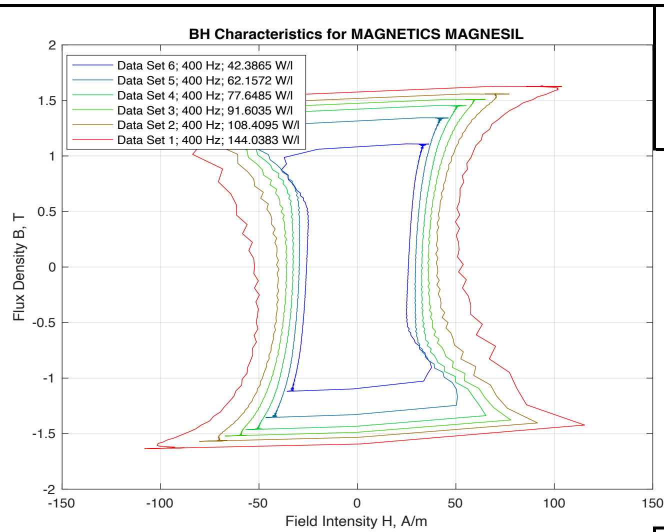


Magnetic Flux Density vs Core Loss - Table

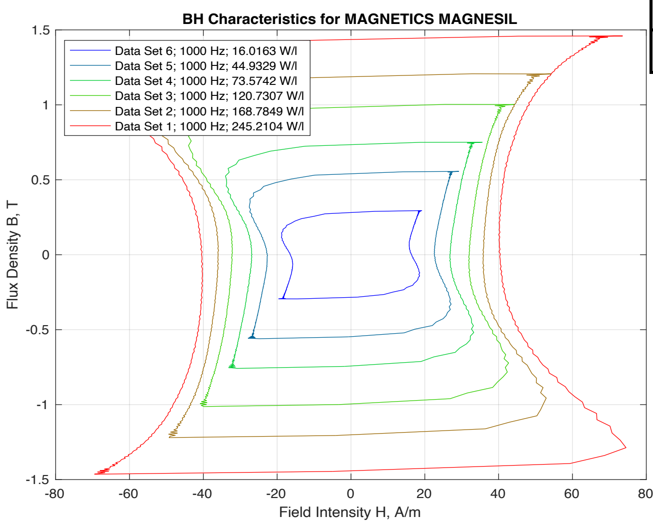
60 Hz		**400 Hz**		**1 kHz**		**10 kHz**	
B (T)	**Core Loss (W/kg)**	**B (T)**	**Core Loss (W/kg)**	**B (T)**	**Core Loss (W/kg)**	**B (T)**	**Core Loss (W/kg)**
1.31	1.10	1.63	21.71	1.61	54.27	0.69	291.57
1.20	0.90	1.56	16.44	1.46	40.97	0.35	92.41
0.94	0.56	1.52	13.93	1.03	20.36	0.18	29.44
0.25	0.08	1.46	11.83	0.80	12.71	0.13	16.83
0.11	0.02	1.34	9.56	0.59	7.41	0.10	9.00
0.06	0.01	1.10	6.57	0.45	4.55	0.06	3.57

50 kHz	
B (T)	**Core Loss (W/kg)**
0.24	609.87
0.17	350.66
0.07	64.33
0.04	27.98
0.03	14.94
0.02	8.83

Empirical Model for Core Loss using Steinmetz Equation: Square Excitation via Sudhoff Simulation



(a)



(b)

Steinmetz Equation

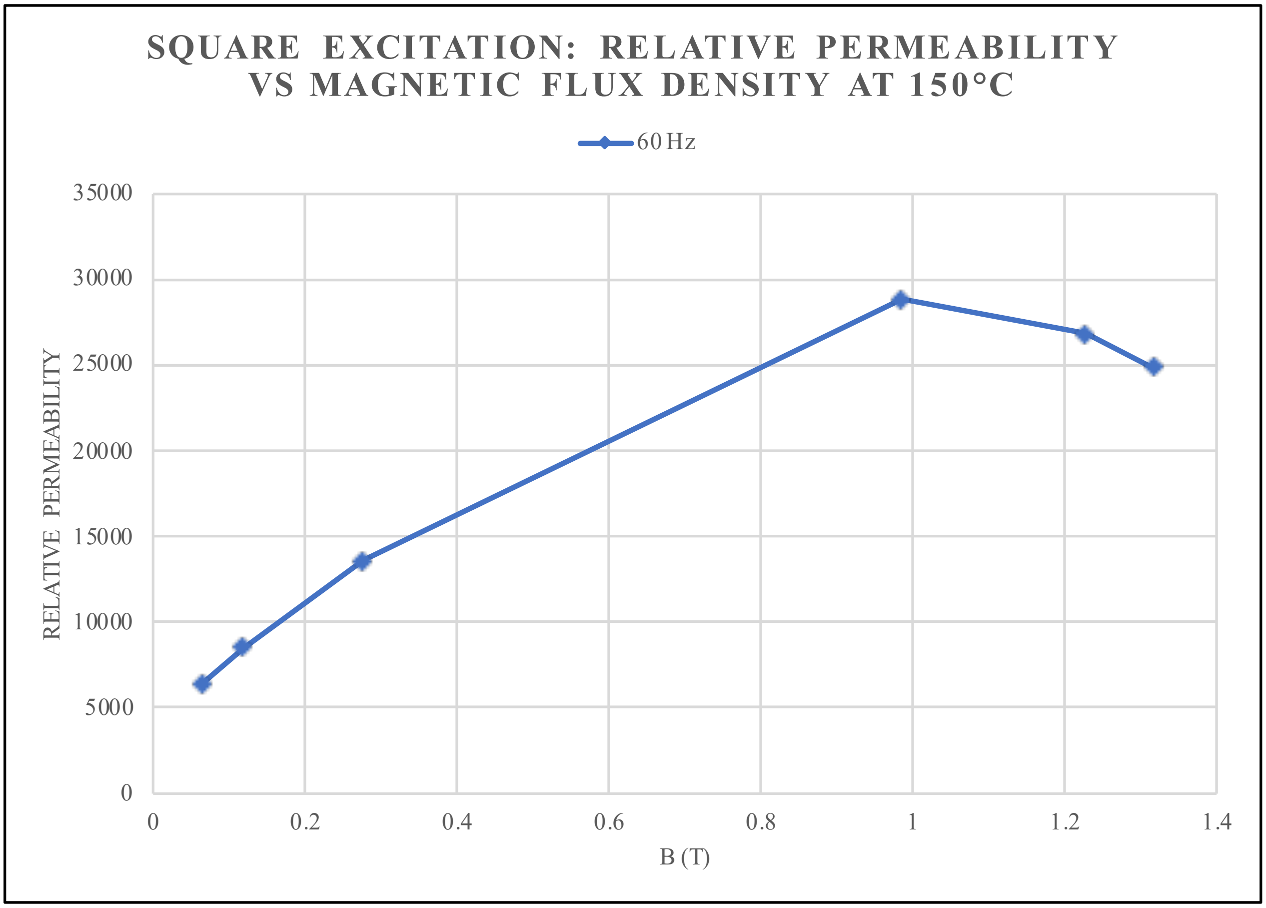
$$p_w = k_h \left(\frac{f}{f_b}\right)^{\alpha}\left(\frac{B_{pk}}{B_b}\right)^{\beta}$$

Steinmetz Coefficients for Curve Fit 100°C

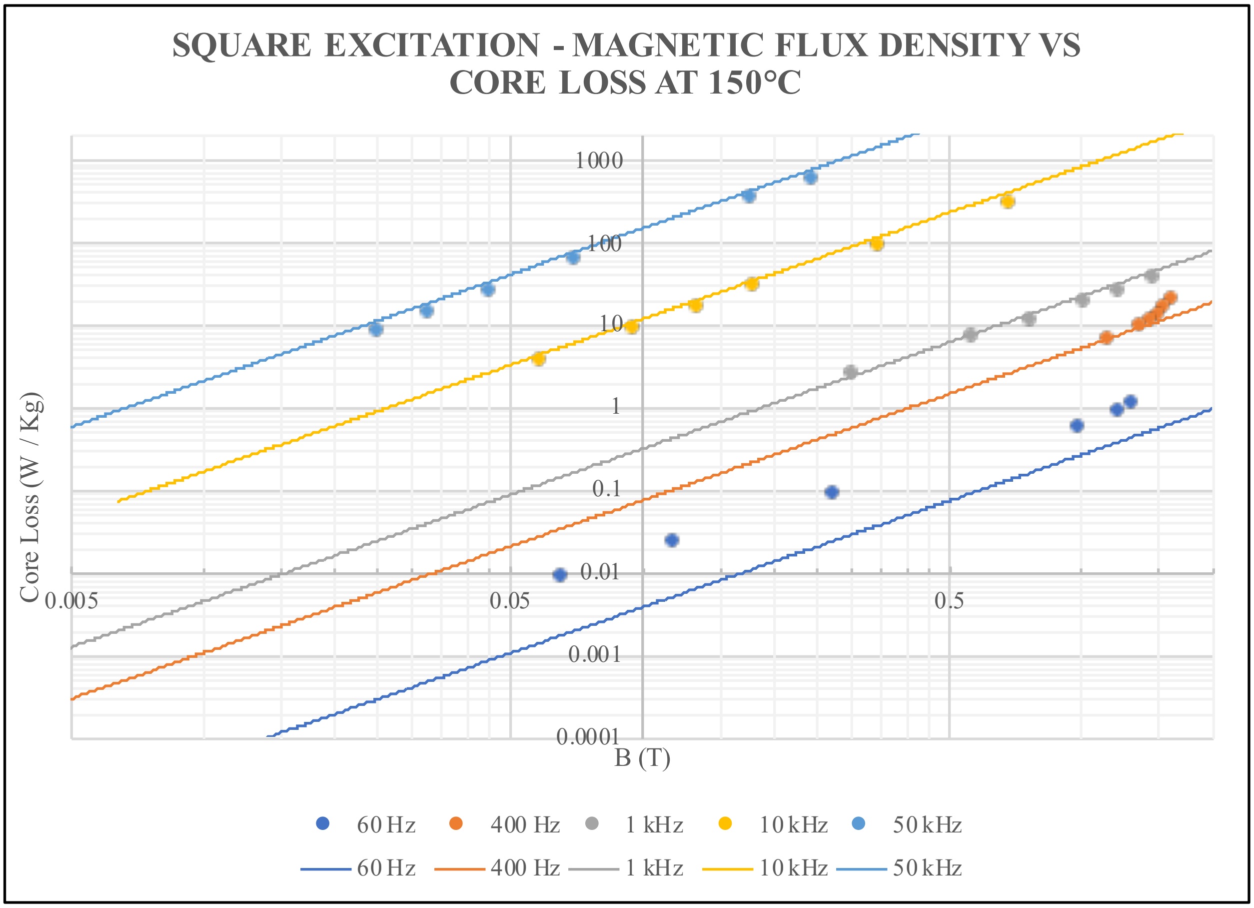
α	1.5827	
β	1.8442	
k_h	0.000410611	W / kg

Empirical Model Plot Sample – (a) 400 Hz. (b) 1 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h, α, and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..



60 Hz	
B (T)	μ_r
1.32	24912.59
1.23	26848.62
0.98	28864.07
0.28	13596.10
0.12	8522.34
0.07	6451.00

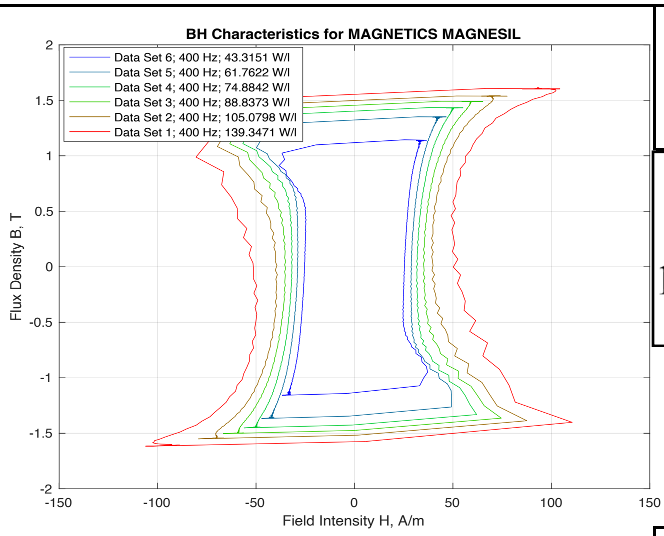


Magnetic Flux Density vs Core Loss - Table

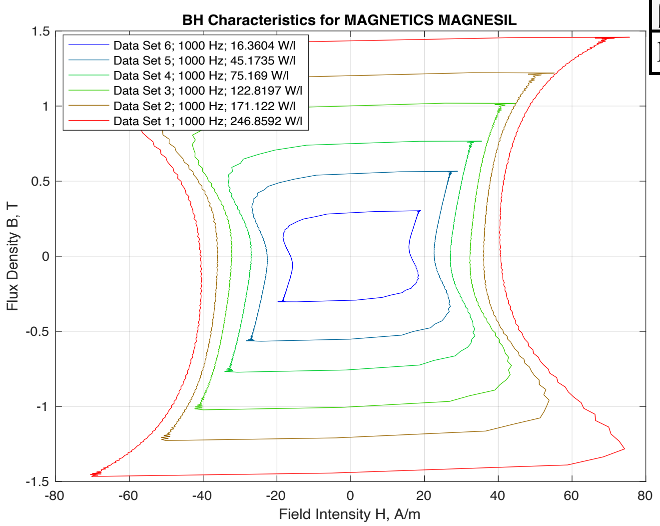
60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	**Core Loss (W/kg)**	**B (T)**	**Core Loss (W/kg)**	**B (T)**	**Core Loss (W/kg)**	**B (T)**	**Core Loss (W/kg)**
1.32	1.09	1.61	21.00	1.46	37.86	0.69	291.57
1.23	0.91	1.55	15.93	1.23	26.26	0.35	92.41
0.98	0.58	1.50	13.50	1.02	18.85	0.18	29.44
0.28	0.09	1.44	11.41	0.77	11.54	0.13	16.83
0.12	0.02	1.36	9.43	0.57	6.93	0.10	9.00
0.07	0.01	1.15	6.62	0.30	2.51	0.06	3.57

50 kHz	
B (T)	**Core Loss (W/kg)**
0.24	582.64
0.18	330.72
0.07	60.03
0.05	25.97
0.03	13.99
0.03	8.37

Empirical Model for Core Loss using Steinmetz Equation: Square Excitation via Sudhoff Simulation



(a)



(b)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b}\right)^{\alpha} \left(\frac{B_{pk}}{B_b}\right)^{\beta}$$

Steinmetz Coefficients for Curve Fit 150°C

α	1.5691	
β	1.8441	
k_h	0.000444607	W / kg

Empirical Model Plot Sample – (a) 60 Hz. (b) 1 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h, α, and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..