An Objective Comparison of Powder Core Materials for Inductive Components with Selected Design Examples

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Abstract

Engineers and magnetics designers need to understand the differences between iron powder and sendust powder core materials. This paper explains the basic performance differences between the two types of powder materials including applications, design examples with cost goals, basic design guidelines and thermal aging.

Discussion

Engineers today are under severe pressure to use the lowest cost core materials and sometimes have not fully understood the subtle differences between iron powder and sendust. As a result, iron powder core materials have gotten a bad rap in recent times due to misapplication or insufficient testing of the prototype that would have uncovered potential thermal lifetime problems with the design.

The purpose of this article is to point out the differences between these commonly used distributed air gap core materials, the importance of using sound design guidelines and available software design tools.

Iron powder is the least expensive magnetic material available and its properties make it well suited for most inductor applications. Its relatively low permeability and high saturation flux density give it high energy storage capabilities with a soft saturation curve. While its core loss properties do not make it a good choice for discontinuous mode flybacks and switching transformers, they are generally acceptable for most inductors. Typical applications include:

- 60 Hz Differential-Mode EMI Chokes
- DC Output Chokes
- Power Factor Chokes (PFC)
- Resonant Inductors
- Hall Effect Sensor Cores
- Boost or Buck Inductors
- Flux-Path or Shunt Cores Placed in Ferrite Gaps to reduce Fringing Flux
- Light Dimmer Chokes

Material Comparison

Figure #1 shows the similarities in DC Saturation characteristics between Micrometals Mix –52 and the 75µ sendust materials. Both core materials are 75µ materials.

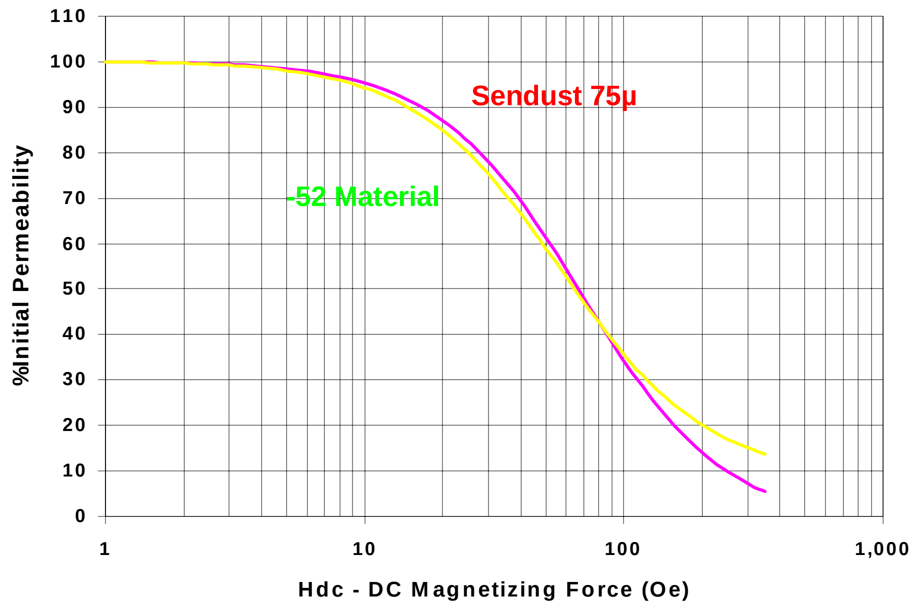

Figure 1: %Initial Permeability vs. Hdc

Figure #2 shows the similarities in DC saturation characteristics between Micrometals Mix –18 (µ = 55) and the 60µ sendust. You can see the saturation characteristics are about the same to 100 Oe and then the iron powder holds up a little better at higher drive levels.

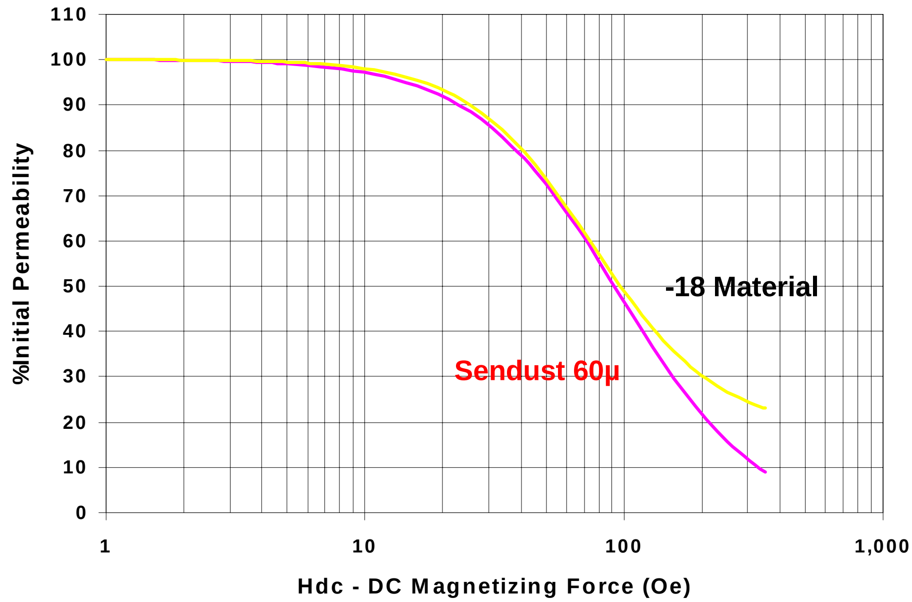

Figure 2: %Initial Permeability vs. Hdc

Since the sendust cores are not available in permeability's below 26, Figure 3 shows the next best comparison using Micrometals Mix –2 with a perm of 10. For applications with very high surge currents, Figure 3 shows that Micrometals Mix –2 is very difficult to saturate and still maintains 100% of its initial inductance at 100 Oe.

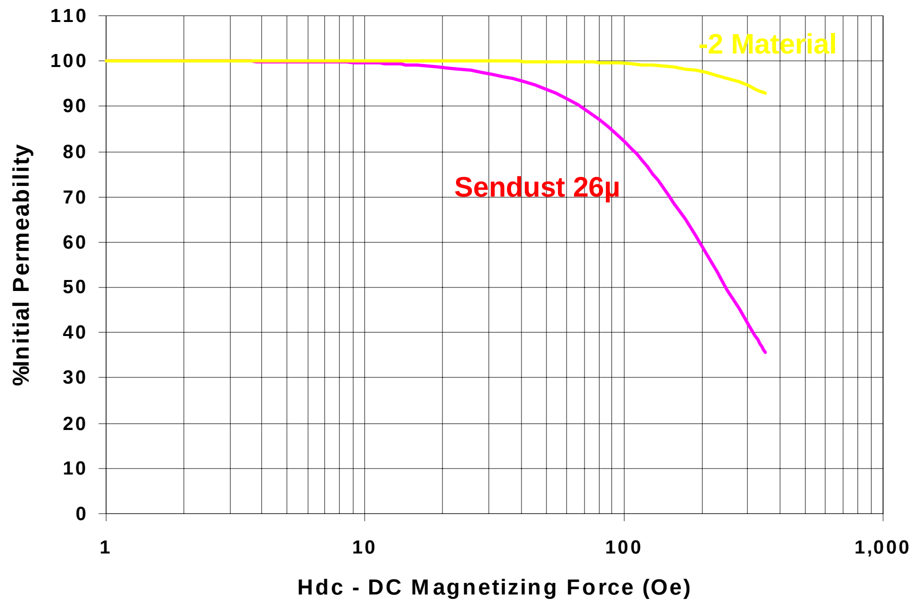

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Figure 3: %Initial Permeability vs. Hdc

One major difference between iron powder and sendust materials is how the initial permeability reacts to increasing Peak AC Flux Density levels.

Figure 4 shows how Micrometals 10μ, 55μ and 75μ materials will change with increasing Peak AC Flux Density. The smallest change is observed with the 10μ material. In comparison, the 26μ sendust material will change about +1% at 500 gauss and the 75μ sendust material will change about +2.0% at 500 gauss.

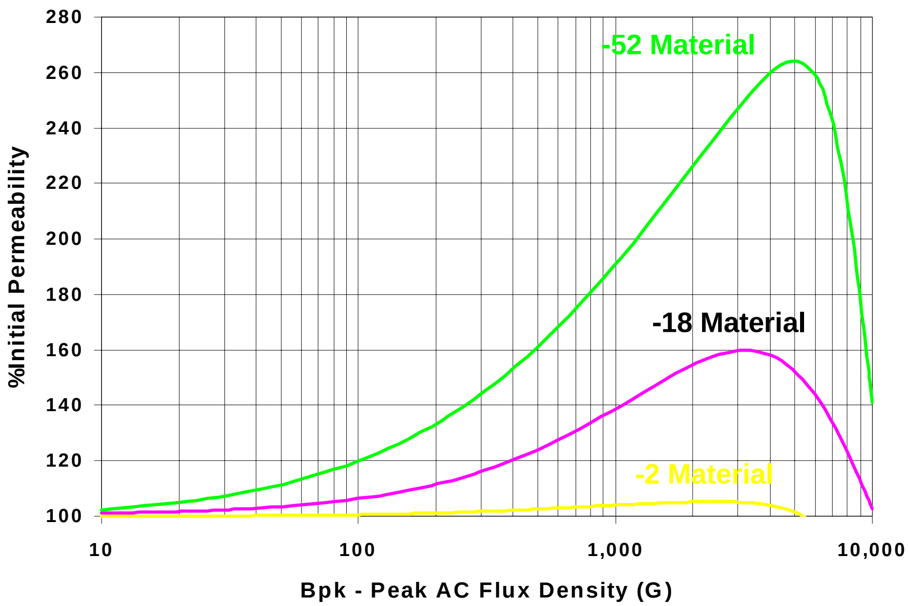

Figure 4: %Initial Permeability vs. Bpk

Figures 5 and 6 shows the core loss at 25 kHz and 100 kHz. In all cases the core loss of sendust is lower than the iron powder materials.

As the frequency of operation increases to 500 kHz, Figure 7 shows the Micrometals Mix –2 core loss to be less than or the same as the sendust.

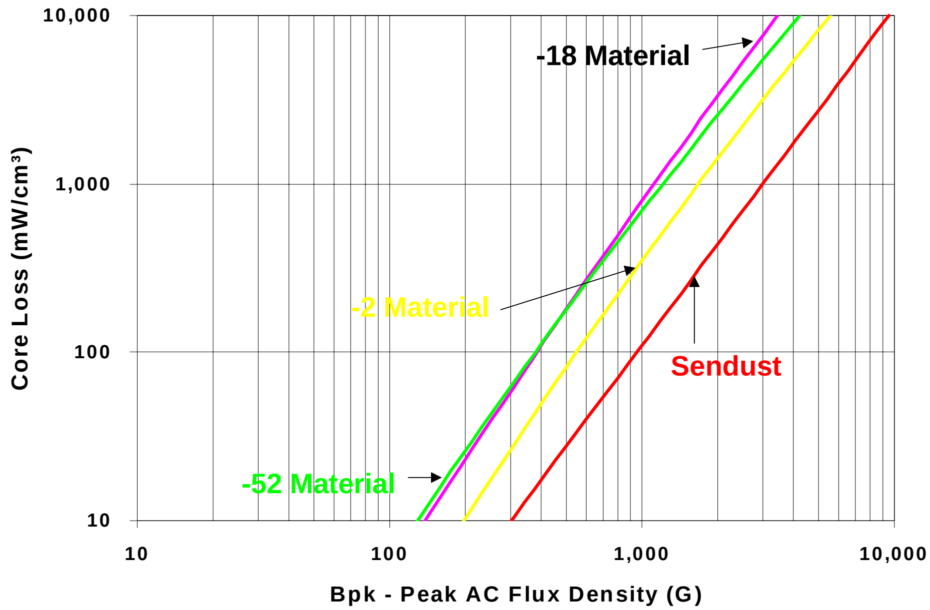

Figure 5: Core Loss vs. Bpk – 25 kHz

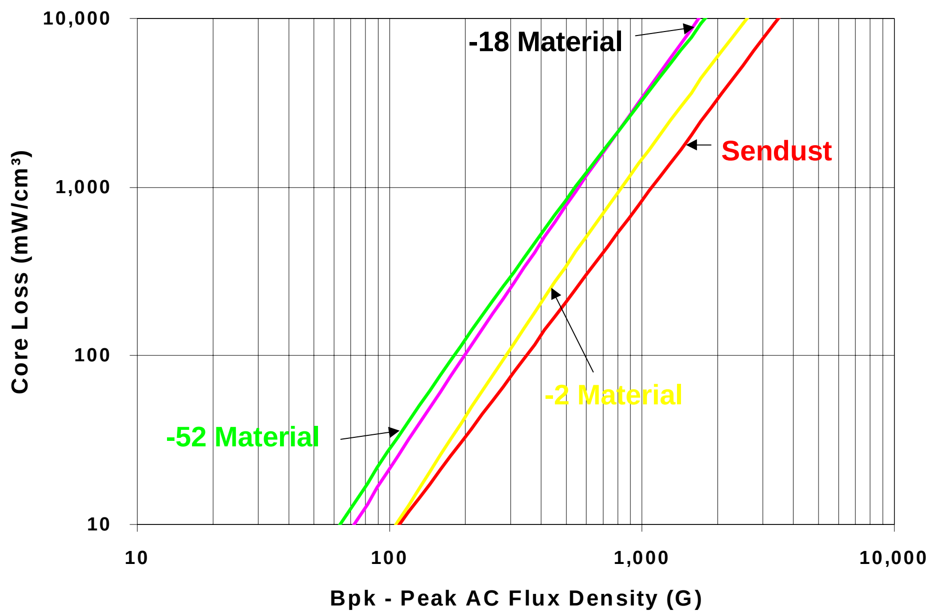

Figure 6: Core Loss vs. Bpk – 100 kHz

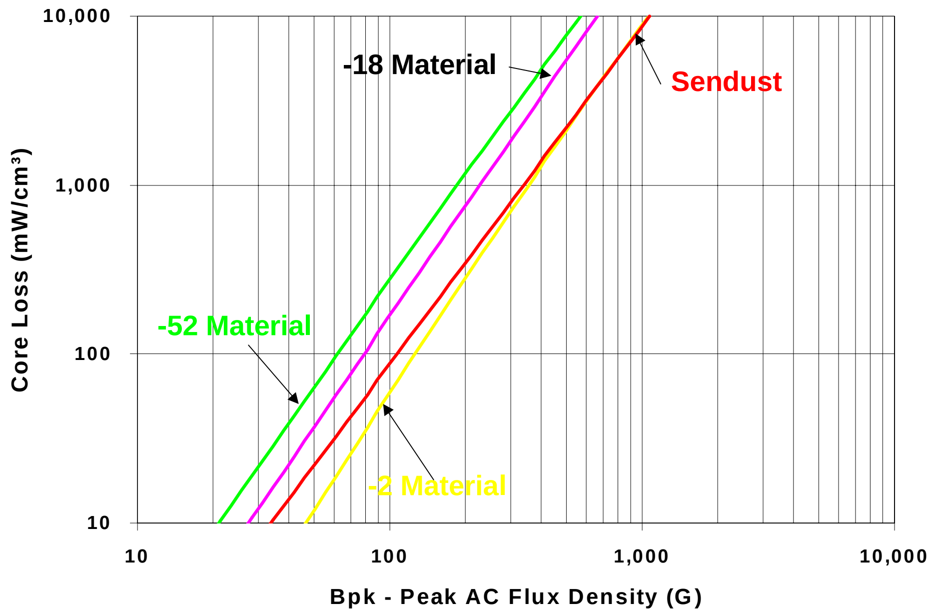

Figure 7: Core Loss vs. Bpk – 500 kHz

Figures 8, 9 and 10 show the differences in initial permeability vs. frequency. These differences are important to be aware of depending on the intended application. As an example, for differential mode inductors, select a core material whose permeability decreases with increasing frequency like the Micrometals Mix –52 or –26. For a broadband inductor application, select a core material whose permeability changes much less with increasing frequency like the lower permeability materials.

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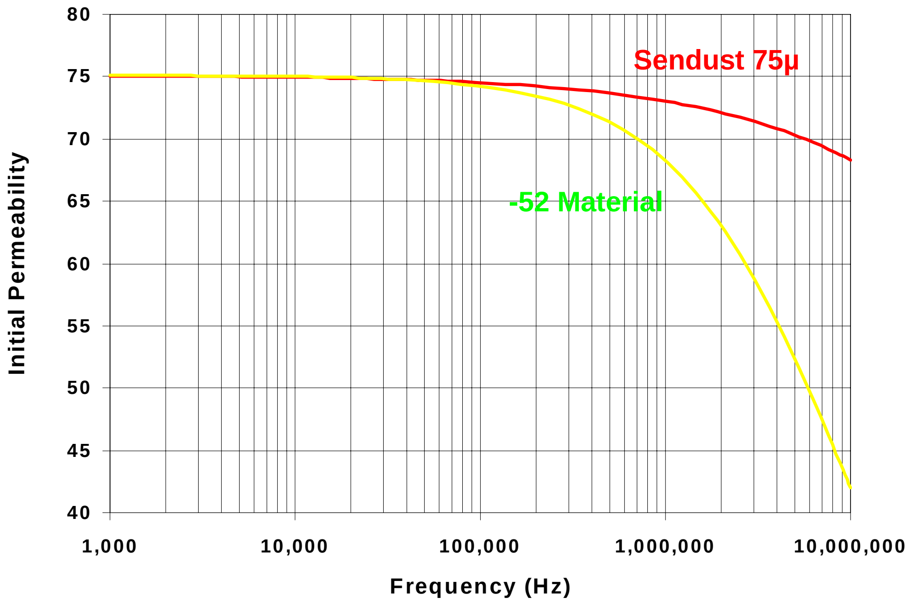


Figure 8: Initial Permeability vs. Frequency

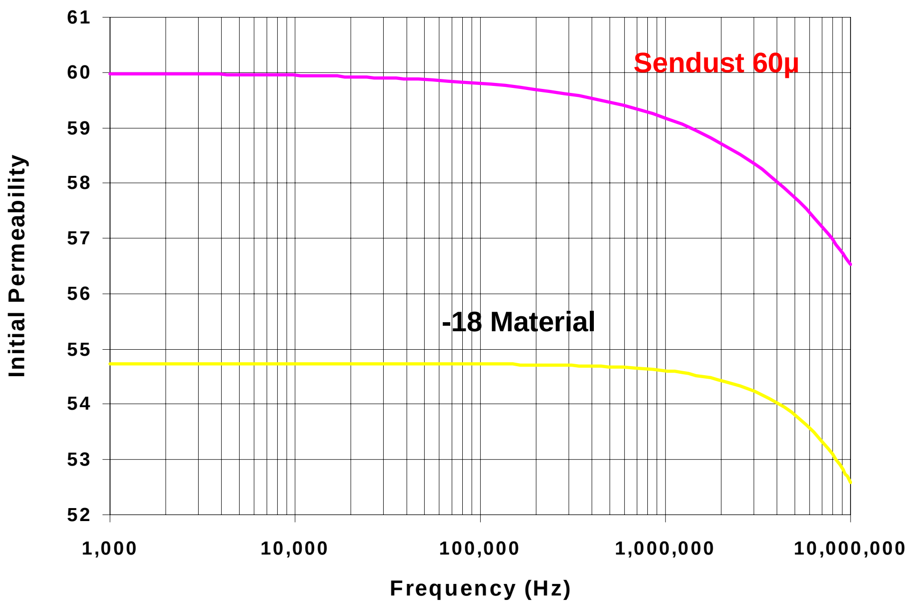


Figure 9: Initial Permeability vs. Frequency

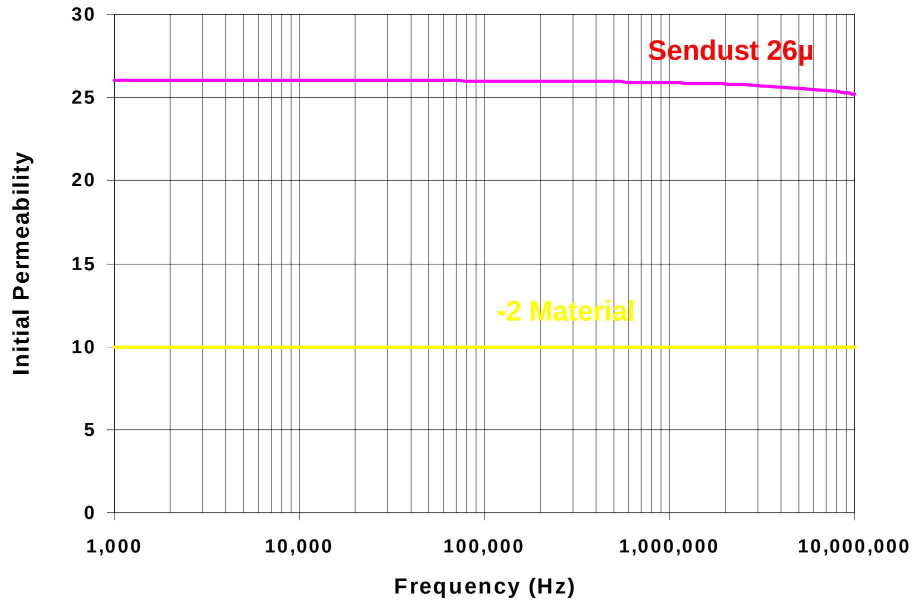
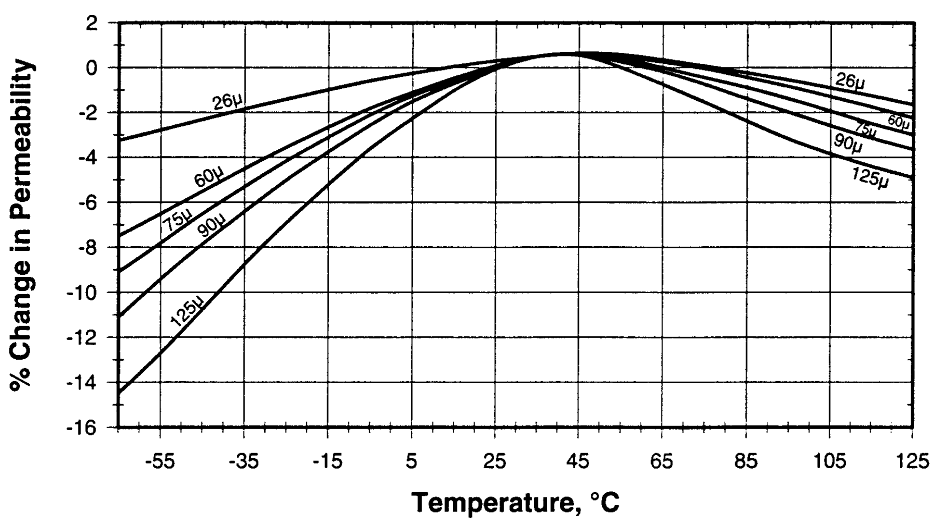


Figure 10: Initial Permeability vs. Frequency

Figures 11 and 12 show the % change in permeability over temperature for the sendust and iron powder materials. You will notice iron powder in all cases has a



positive Tc over temperature.

Figure 11: %Change in Permeability vs. Temperature – Sendust

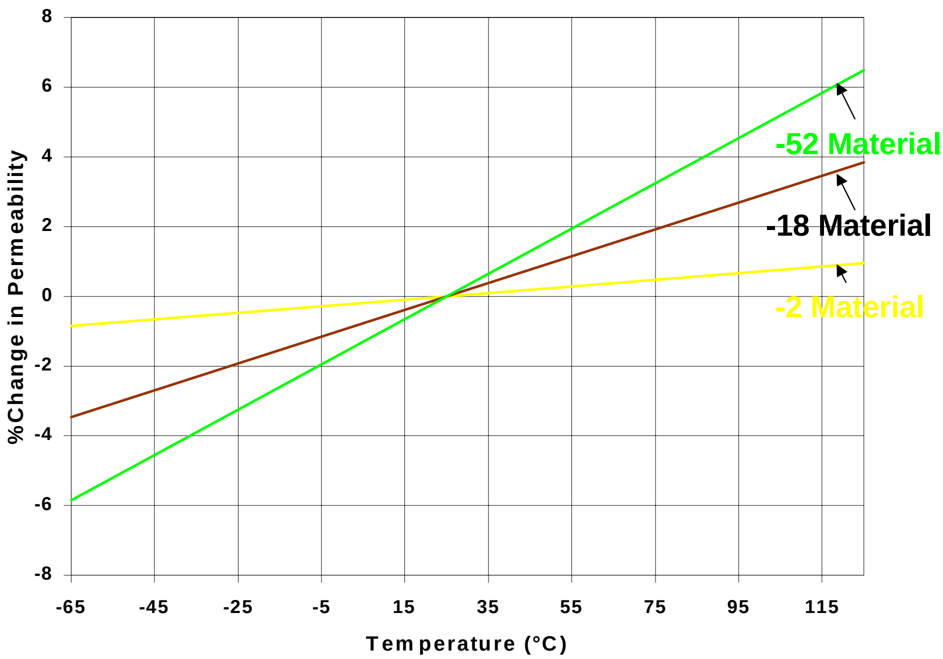


Figure 12: %Change in Permeability vs. Temperature – Iron Powder

Design Examples

The following design examples will illustrate differences in the powder core material losses and when they are important or not important.

60 HZ Differential Mode Design Example Comparison

A comparison of these materials in a 60 Hz differential mode choke requiring a minimum of 50 µH at 12 amperes follows:

Design Requirements:

• Minimum Inductance	50 µH
• DC Current	12 A
• Frequency	60 Hz + HF Noise
• Maximum Size	1.25” OD
• Maximum Temp. Rise	55 C°
• Target Core Cost	$0.20

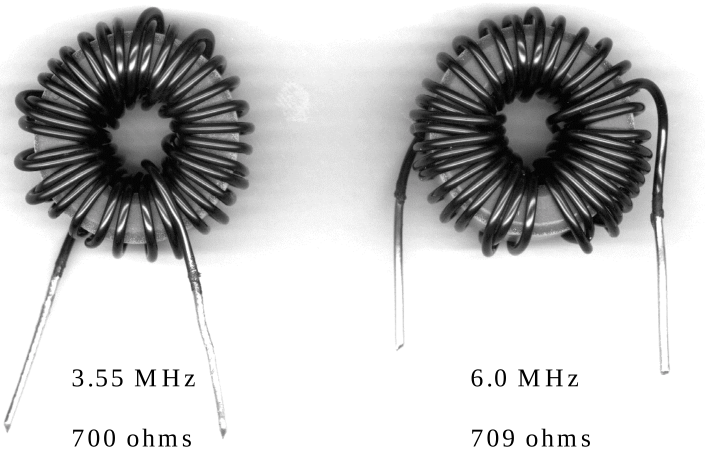
Table 1: Differential Mode Design Example

	Iron Powder	Sendust
Part Number	T106-52	77935-A7
AL (nH/N²)	95	94
Turns	35	35
AWG#	16	16
Bpk @ 60 Hz (G)	2,571	2,571
Core Loss (mW/cm³)	9.1000	0.1086
Core Volume (cm³)	4.28	4.15
Core Loss (mW)	39.000	0.451
Copper Loss (mW)	3,230	3,230
Total Loss (mW)	3,269	3,230
Wound Surface Area (cm²)	31	31
Maximum Size (in)	1.2	1.2
ΔT (C°)	49	48
Approx. Core Cost (per piece)	$0.14	$0.90
OD (in)	1.06	1.06
ID (in)	0.57	0.58
Ht (in)	0.437	0.44

This shows that while the core loss characteristics of the sendust are significantly lower than the iron powder that in this application it is not one of the controlling factors and only saves 1C° in temperature rise. However the difference in cost is very significant with the iron powder core at $0.14 compared to $0.90 for the sendust.

In this type of application where it is necessary to suppress high frequency noise, the winding details can have a profound impact on the performance. Figure 13 shows impedance vs. frequency results for the iron powder coil with a 720° (twice around) winding and a progressive/backwound winding (once around):

DIFFERENTIAL MODE INDUCTORS
IMPEDANCE TEST RESULTS OF TWO WINDING CONFIGURATIONS
MICROMETALS P/N T106-52 WOUND WITH 35 TURNS OF AWG-16



SRF	3.55 MHz	6.0 MHz
Z @ 1MHz	700 ohms	709 ohms
Z @ 10MHz	828 ohms	2.99K ohms
Z @ 20MHz	250 ohms	1.014K ohms
Z @ 30MHz	205 ohms	472 ohms
Z @ 40MHz	132 ohms	890 ohms

Figure 13: Differential Mode Inductor Winding Types

The progressive/backwound part produces significantly greater impedance at the higher frequencies by minimizing the capacitive effects in the winding.

Buck Inductor Design Comparison

The second comparison is for a buck inductor with the following design requirements:

Design Requirements

• Minimum Inductance	4.0 μH
• DC Current	18 A
• Frequency	100 kHz
• Epk Input	5V
• EDC Output	3V

The two designs compare as follows:

Table 2: Buck Inductor Design Example

	Iron Powder	Sendust
Part Number	**T68-52A**	**77225-A7**
AL (nH/N²)	**54**	**43**
Turns	**12**	**13**
AWG#	**14**	**14**
Bpk @ 100 kHz (G)	**323**	**375**
Core Loss (mW/cm³)	**343**	**117**
Core Volume (cm³)	**1.030**	**0.789**
Core Loss (mW)	**354**	**92**
Copper Loss (mW)	**1,347**	**937**
Total Loss (mW)	**1,701**	**1029**
Wound Surface Area (cm²)	**13.3**	**12.0**
Maximum Size (in)	**0.825 x 0.425**	**0.825 x 0.425**
ΔT (C°)	**57**	**41**
Approx. Core Cost (per piece)	**$0.07**	**$0.41**
OD (in)	**0.69**	**0.65**
ID (in)	**0.37**	**0.4**
Ht (in)	**0.25**	**0.25**

This shows the iron powder coil is larger with a total loss of 1.70 watts and a temperature rise of 57C° compared to a total loss of 1.03 watts and a temperature rise of 41C° for the sendust. With the iron powder core at $0.07 and the sendust at $0.41, the sendust should only be used when size and efficiency take priority over cost.

Thermal Aging

If this design must operate in a 55°C ambient, the iron powder core will run at 112°C. Since iron powder cores undergo thermal aging it is essential to consider the long-term effects of operating under these conditions. Micrometals has developed the ability to provide such a thermal aging profile as shown:

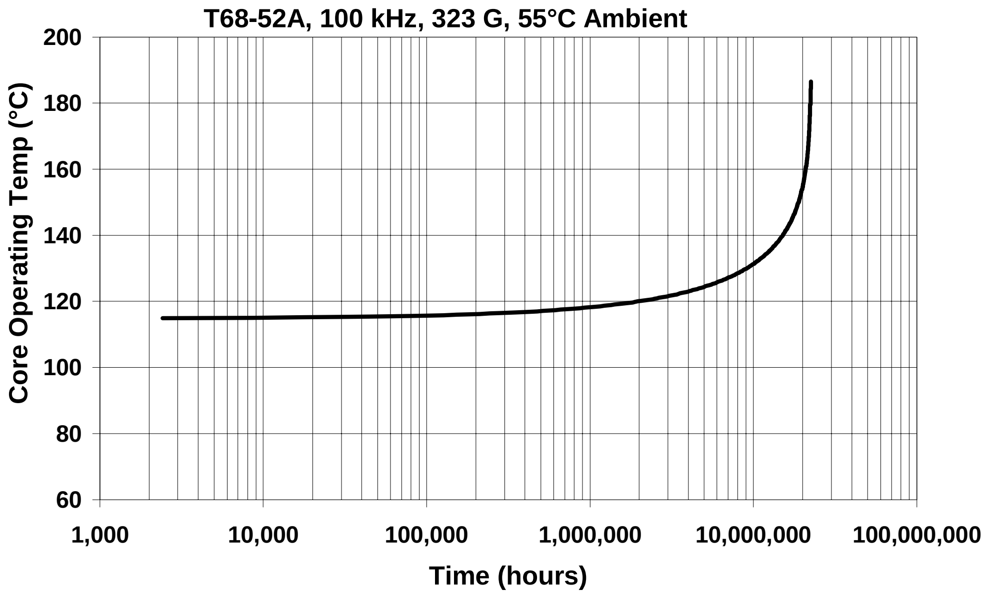


Figure 14: Core Operating Temperature vs. Time

This shows the core will operate reliably for well beyond 1 million hours (114 years).

It required a great deal of time and effort for Micrometals to gather the data and develop the models required to make these predictions, and the results are only valid for cores manufactured by Micrometals. Micrometals has encountered numerous situations where a Micrometals core will operate reliably in a design and a competitor's core will not. A specific case in point is illustrated in Figure 15:

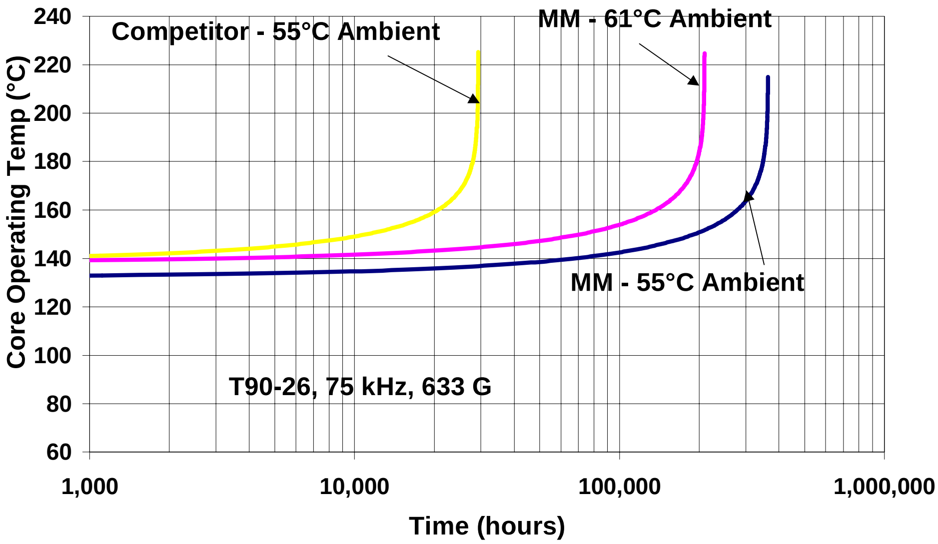


Figure 15: Core Operating Temperature vs. Time

This shows that the competitor's core has somewhat higher core loss causing it to operate at a maximum temperature of 139°C where the Micrometals core starts at 132°C. We characterized the competitor's thermal profile and found that it was dramatically worse than for the standard Micrometals core. This results in thermal runaway of the competitor's core after less than 30,000 hours where the Micrometals core will operate for over 300,000 hours. Even if the ambient temperature is raised on the Micrometals core to create an initial starting temperature equal to the competitor's core, the Micrometals core will last almost 7 times longer.

This illustrates that while the competitor's core will pass incoming inspection and initial burn-in of the power supply, it will fail after less than 2 years in the field. This is just what is happening and has created an enormously expensive recall problem.

60 Hz Dimmer example

Design Requirements

• Minimum Inductance	1.6 mH
• RMS Current	12 A
• Frequency	60 Hz
• Maximum Size	2.75" OD
• Maximum Temp. Rise	85°C
• Target Core Cost	$0.65

The 60Hz inductor design is very similar to the Differential mode inductor since the both are driven to higher peak AC flux levels at 60 Hz. In addition, the iron powder core material will do a better job suppressing the high frequency noise due to its loss characteristics.

Table 3: 60 Hz Dimmer Design

	Iron Powder	sendust-type
Part Number	**T225-26**	**77214-A7**
AL (nH/N²)	**98**	**94**
Turns	**143**	**130**
AWG#	**14**	**14**
Bpk @ 60 Hz (kG)	**11.2**	**14.3**
Core Loss (mW/cm³)	**139.00**	**3.34**
Core Volume (cm³)	**20.70**	**20.65**
Core Loss (mW)	**2,770**	**69**
Copper Loss (mW)	**12,250**	**11,220**
Wound Surface Area (cm²)	**110**	**110**
Maximum Size (in)	**2.55**	**2.55**
ΔT (C°)	**61**	**49**
Approx. Core Cost (per piece)	**$0.56**	**$3.80**
OD (in)	**2.25**	**2.25**
ID (in)	**1.405**	**1.4**
Ht (in)	**0.55**	**0.55**

In reviewing the two designs, the 12 C° difference has no impact on the operational lifetime and the clear choice is to select the iron powder core. The design engineer has just saved approximately $3.24 in core cost by selecting the T225-26 iron powder core.

PFC Chokes

Another popular application for iron powder cores is PFC boost chokes. This can be a very demanding application where core loss calculation is more complex and often misunderstood. This can lead to poor designs that will have reliability problems. Micrometals has an application note, which addresses proper core loss analysis for PFC boost chokes as well as design software that covers this application.

Consider the following design example:

Design Requirements

- Minimum Inductance 250 µH
- Peak Current 7 A
- Frequency 100 kHz
- Epk Input 120V
- EDC Output 400V

Table 4: PFC Choke Design Comparisons

	#1	#2	#3
Part Number	**E168-52**	**E168-52**	**E168-2**
AL (nH/N²)	**179**	**179**	**44**
Turns	**45**	**90**	**76**
AWG#	**14**	**17**	**16**
Bpk @ 100 kHz (G)	**389**	**195**	**230**
Core Loss (mW/cm³)	**489.0**	**120.0**	**61.5**
Core Volume (cm³)	**18.5**	**18.5**	**18.5**
Core Loss (mW)	**9,063**	**2,220**	**1,137**
Copper Loss (mW)	**866**	**3,480**	**2,324**
Total Loss (mW)	**9,929**	**5,700**	**3,461**
Wound Surface Area (cm²)	**66.7**	**66.7**	**66.7**
Maximum Size (in)	**1.7 x 1.7**	**1.7 x 1.7**	**1.7 x 1.7**
ΔT (C°)	**65**	**41**	**27**
Approx. Core Cost (per piece)	**$0.23**	**$0.23**	**$0.55**
Thermal Life (Hours)	**<12,000**	**~1,000,000**	**>10,000,000**

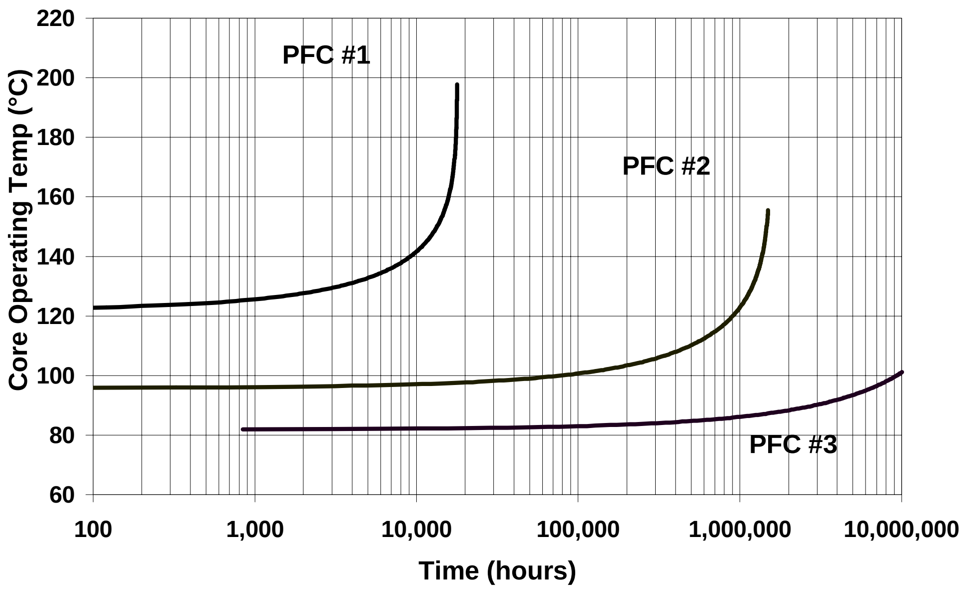


Figure 16: Core Operating Temperature vs. Time – PFC Designs

Example #1 is a design that is dominated by 9.06 watts of core loss with only 0.87 watts of copper loss. This results in a temperature rise of 65C°. With an ambient of 55°C, this part will have thermal runaway in less than 2 years.

Example #2 shows that with the same core, by simply increasing the number of turns with the required smaller wire size, the core and copper losses will become more balanced. This results in improved efficiency (saves 4.3 watts), a lower operating temperature (ΔT=24C°), and a dramatic improvement in thermal life (almost 2 orders of magnitude). While it may seem obvious that example#1 is a poor design, this is a fairly common mistake.

If the higher inductance produced by adding turns in example #2 is unacceptable in the circuit, the core and copper losses can also be better balance by selecting a lower permeability material. Example #3 illustrates how the Micrometals 10μ -2 material performs. This choke will be the most efficient and reliable, but this grade of material is somewhat more expensive than the –52 Material.

While Micrometals can provide the tools to make the illustrated thermal life predictions, this information will only be valid upon experimental verification of the actual worst case operating temperature. Where a fan is being used to help reduce temperatures, measurements need to be taken at various locations to find the worst-case hot spot. This can accomplished by drilling a small hole in the core to accept a thermocouple. The actual operating temperature may be somewhat higher or lower than predicted depending on the exact environment. It is recommended that an adjustment equal to this difference be made in the ambient temperature and then re-run the thermal life prediction.

It is also important to be extremely careful with the use of variable speed fans. Often these fans will move less air at lower power levels. Unfortunately, in most designs the core loss does not decrease at lower power levels, so in a core loss dominated design it is possible to have a choke actually run hotter at low power than it will at high power.

Basic Design Rules

The maximum ambient temperature will set the upper temperature rise limitation of the design based on the previous thermal aging discussion.

Start the design with 50/50 division of core loss to copper loss. Complete the design so the copper loss is dominant because it is always easier to remove heat from the winding than the heat in the core material.

Use the Micrometals design software Thermal Aging feature to help guide your selection of design solutions that will meet the operational lifetime parameters. Consult the Micrometals office in Anaheim, California if you have any questions about your design or application. When using the design software, make sure the ambient temperature default has been adjusted for your application. The default is preset to 25 C °.

If forced air flow is available, make sure the fan is not a "variable speed" type that changes speed and airflow based on output power delivered by the power supply. This becomes a critical issue if the core loss is high and the fan is relied upon to reduce the temperature. Many inductor applications today have constant core loss regardless of the load current.

Validate the design by making careful thermal measurements of the internal core temperature and coil temperature. Last but not least, do not be afraid to ask questions if you do not fully understand magnetics design. Micrometals offers free applications help.

Conclusion

Iron powder is a very cost-effective solution for a wide variety of inductors in power conversion and EMI filtering applications. It has been shown that their proper application is essential to insure long term reliability.

Micrometals has developed an updated version of the design software that includes thermal aging predictions that are only valid for Micrometals cores. As more an more competitors attempt to confuse the user by copying Micrometals color codes, it is more important than ever to properly control your supply chain to insure that only cores with proven reliability are used.

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