



Designing with Magnetic Cores at High Temperatures

All cores are not the same. Designers need to know the differences in order to make the best choices.

Thermal considerations are a basic part of power electronics design. Components can be heated by external sources, and they can be heated by their own energy losses. Inductors and transformers are often designed for significant temperature rise in order to optimize cost, size, and performance therefore it is important for the magnetics designer to understand the behavior of magnetic cores at elevated temperatures. Having this understanding is vital for selecting the best type of material for each application, and for ensuring that the magnetic device will function safely at its maximum operating temperature.

POWDER CORES

The **POWDER CORES** made by MAGNETICS® are AmoFlux®, XFLUX®, MPP, Kool M μ ®, and High Flux. All five materials exhibit excellent stability and reliability at high temperatures. Because of the distributed air gap in a powder core, the inductance shift with temperature change is relatively small. Due to the high Curie temperatures of powder core alloys, changes in saturation characteristics are minor over normal operating temperature ranges. Also, powder cores are resistant to thermal shock. AmoFlux is rated to 155°C while MPP, Kool M μ , High Flux and XFLUX are rated for continuous operation up to 200°C.

NO THERMAL AGING – Magnetics powder cores have an advantage over iron powder cores –no thermal aging. The parts are pressed with a non-organic insulating material; no binder is used. Therefore, there are no aging effects, even when the cores are operated continuously at high temperatures.

FERRITE CORES

MAGNETICS' **FERRITE CORES** are manufactured in seven standard materials. Each material has been engineered to satisfy particular application needs. (1) The five power materials exhibit low core losses, and core loss minimums at favorable temperatures and frequencies. (2) The two high permeability ferrites show increasing permeability with increasing temperature. (3) The three filter materials are designed for predictable or minimal inductance shift over a range of temperature.

Designers need to be aware of ferrite magnetic property changes with temperature and that all ferrites are susceptible to thermal shock.

TAPE WOUND CORES

MAGNETICS manufactures **TAPE CORES** in a wide variety of materials and sizes. Tape cores can be placed in aluminum or nylon cases for very rugged environments and 200°C operation.

Tape core alloys generally have high Curie temperatures along with small, predictable shifts in magnetic properties across typical temperature ranges. They are often the best choice for very high temperature environments.

CHOICES, CHOICES

There are many considerations to be made when selecting the best core and material for a given application. Thermal performance is one of the most critical aspects of magnetic design. The designer needs to have a good understanding of the temperature advantages – and the disadvantages – of each material, all of which will be discussed in the following pages.

POWDER CORE TEMPERATURE PROPERTIES

MAGNETICS produces five types of powder cores. All five have excellent high temperature performance.

MPP (molypermalloy powder) cores are made from an alloy of 80% nickel, 20% iron. The metal is ground into fine particles which are then coated with a non-organic, non-magnetic insulating material. The resulting powder is annealed at temperatures above 500°C, and finally pressed into toroids of a variety of sizes. The toroids are annealed above 500°C to relieve stresses. Finished toroids are coated with a gray epoxy paint to provide dielectric protection and extra physical mechanical strength.

Kool M μ cores are made from an alloy of iron, silicon and aluminum. Kool M μ processing is similar to that of MPP cores, including powder annealing and core annealing above 500°C. Kool M μ toroids are also coated with epoxy paint, except in black color. Kool M μ is also available in E-cores, U-cores, segments and blocks with the similar temperature characteristics and performance. Shapes have slightly different DC Bias characteristics due to the differing geometry.

High Flux cores are made from an alloy of 50% nickel, 50% iron. Its manufacture is similar to that of MPP, including the 500°C anneals of powder and toroids. High Flux cores are coated with the epoxy paint, except in khaki color.

AmoFlux is a powder alloy distributed gap material. It starts with low core loss ribbon that is pulverized into powder and then pressed into a toroid. By converting the ribbon into a powder, the resulting AmoFlux cores have the same excellent properties, including soft saturation, as Magnetics other powder core materials. What makes the amorphous powder core material unique is the combination of low core loss and high DC bias. The operating temperature range is -55°C to 155°C. AmoFlux toroid cores are coated with blue colored epoxy coating.

XFLUX distributed air gap cores are made from 6.5% silicon iron powder and are available in 26 μ and 60 μ . A true high temperature material, XFLUX offers lower losses than powder iron cores and superior DC Bias performance. These cores are available in toroids, E cores and blocks. The toroids are epoxy coated and brown in color.

The maximum temperature rating for MPP, High Flux, Kool M μ , and XFLUX powder core types is 200°C. AmoFlux is 155°C. The constraint is the epoxy coating, which is rated to 155°C or 200°C. In most circuits, there are many other components that would fail at lower temperatures, so the core is rarely the limiting factor. Inductors wound on MAGNETICS powder cores can withstand soldering operations that exceed the maximum rated temperature if care is taken in the design of the process to reasonably protect the core. Some applications even use potted inductors in excess of the rated maximum temperature, because the magnetic material itself is not damaged or aged, even at temperatures that are too high for the coating.

There is no aging effect when MPP, Kool M μ , High Flux, XFLUX or AmoFlux cores are operated at elevated temperatures. This is often an advantage when compared with iron powders. The MAGNETICS powder core materials do not contain an organic binder, and therefore are not subject to the thermal

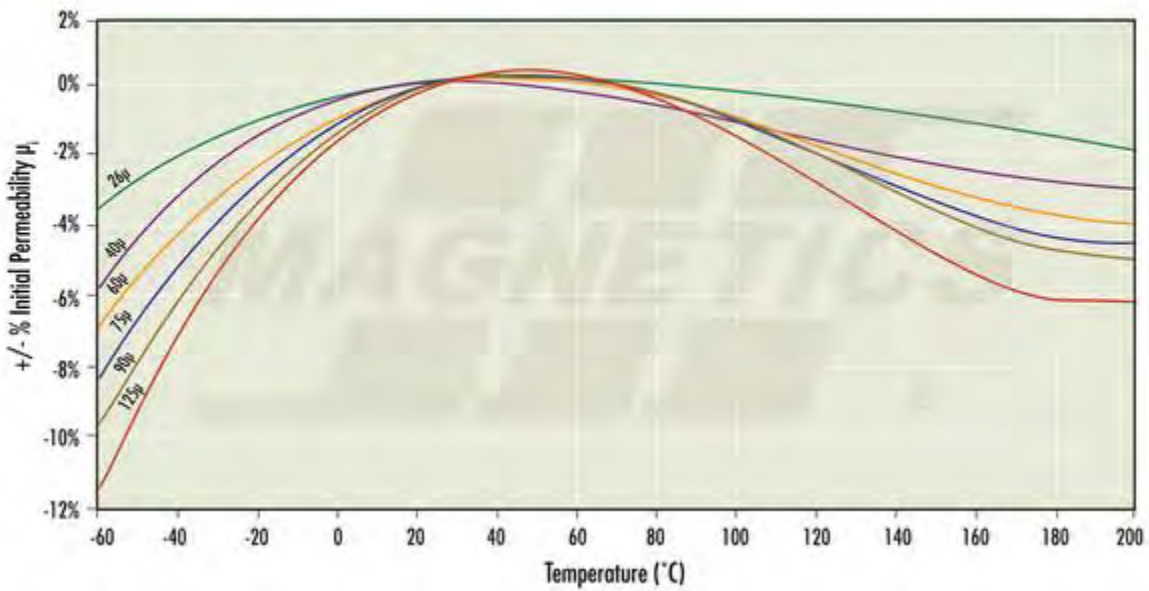
aging phenomenon seen in iron powder materials. (In general, the main advantage of MPP, Kool M μ , High Flux, XFLUX and AmoFlux cores is that core losses are much lower than with iron powder. They are also more stable with changes in temperature, frequency and drive level.)

The magnetic properties of powder cores shift only slightly at high temperatures. The small changes in permeability, DC bias response, and core loss are reversible. When the materials are returned to room temperature, the magnetic properties return to their initial values, no matter how many times the cycle is repeated.

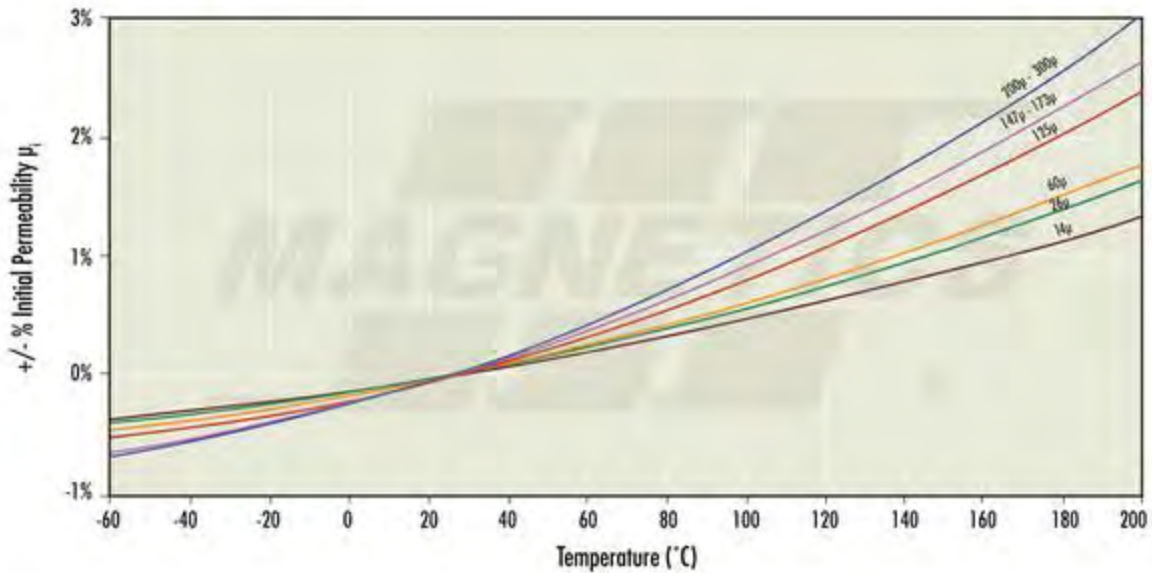
Permeability vs. Temperature

The inductance shift with changing temperature in the powder cores is relatively small. This is largely due to the distributed gap, as well as to the stability of the alloys used. The following graph shows the typical change in inductance over temperature for Kool M μ , MPP, High Flux, XFLUX, and AmoFlux. The shifts are predictable and repeatable.

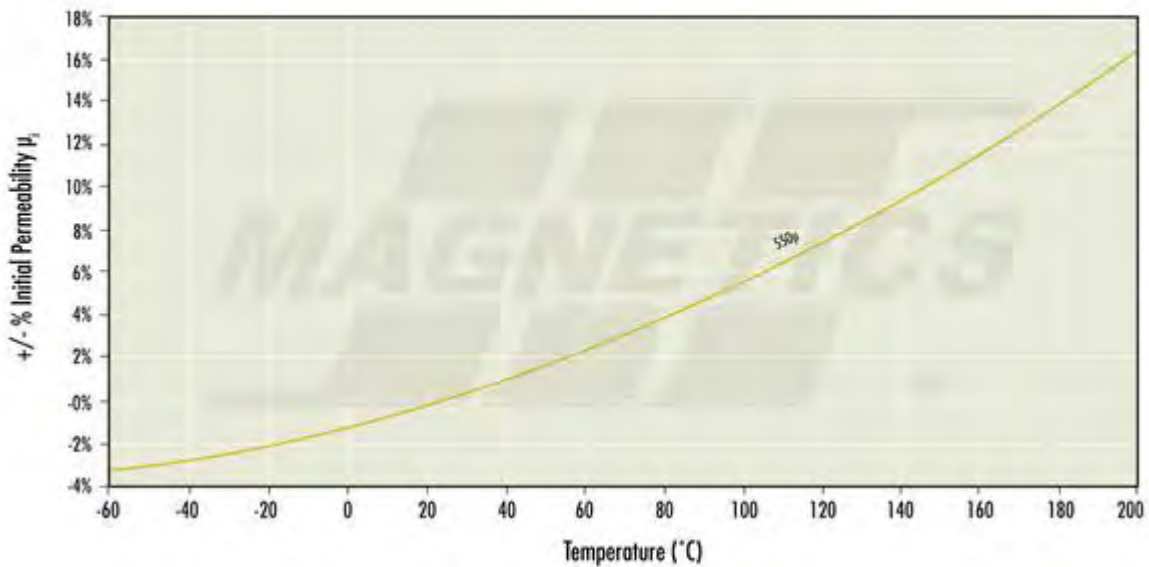
Permeability versus Temperature Curves
Kool M μ [®]



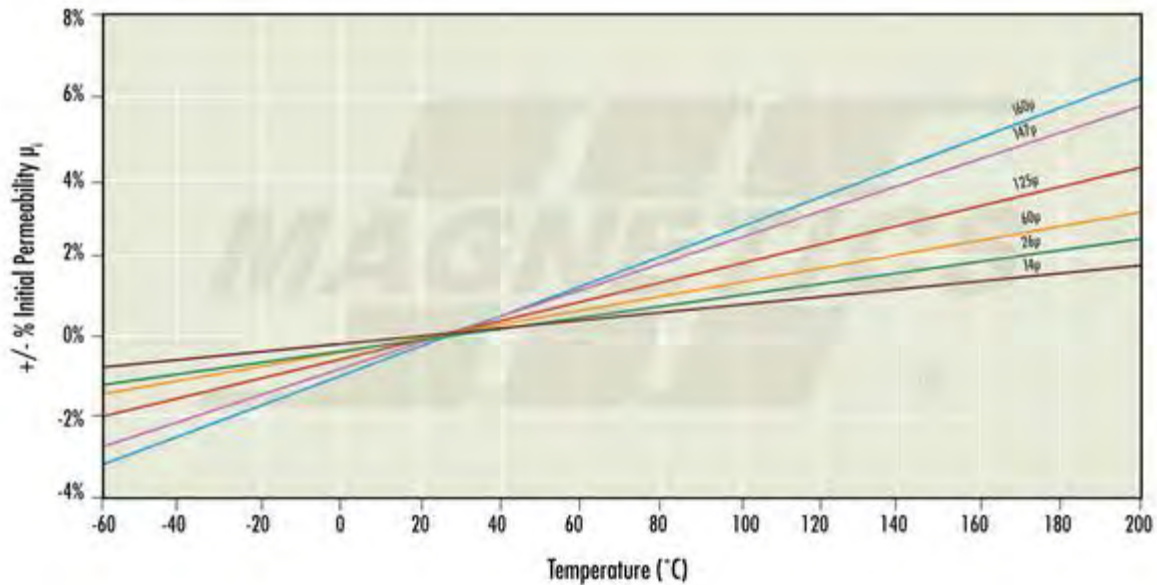
Permeability versus Temperature Curves MPP 14 μ -300 μ



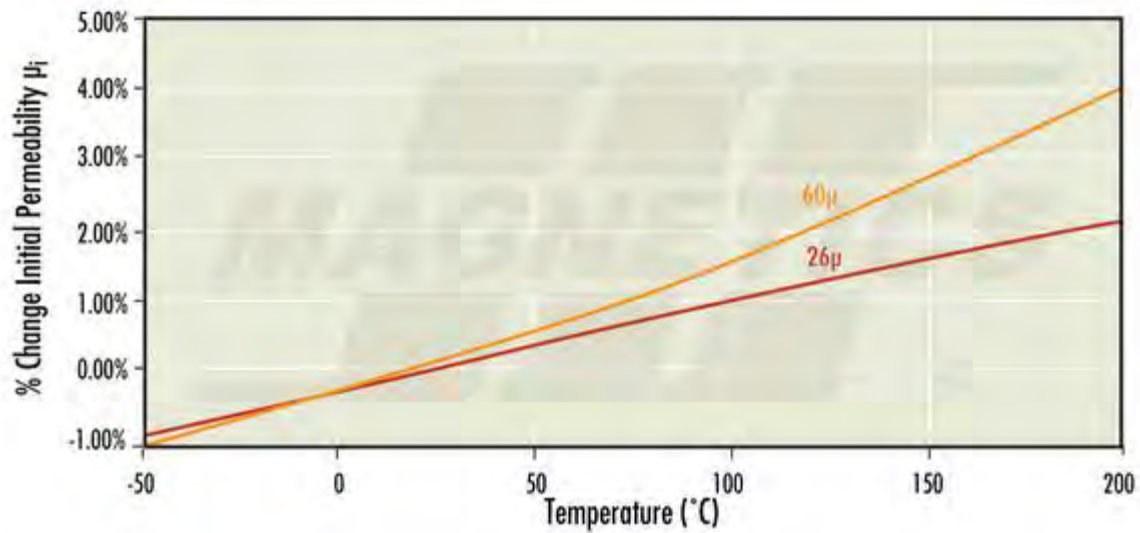
Permeability versus Temperature Curve MPP 550 μ



Permeability versus Temperature Curves High Flux



XFlux[®] Permeability vs. Temperature



AmoFlux Permeability vs. Temperature

$$(\Delta\mu/\mu_i) = -1.014E-02 + 5.222E-04 T - 1.491E-06 T^2$$

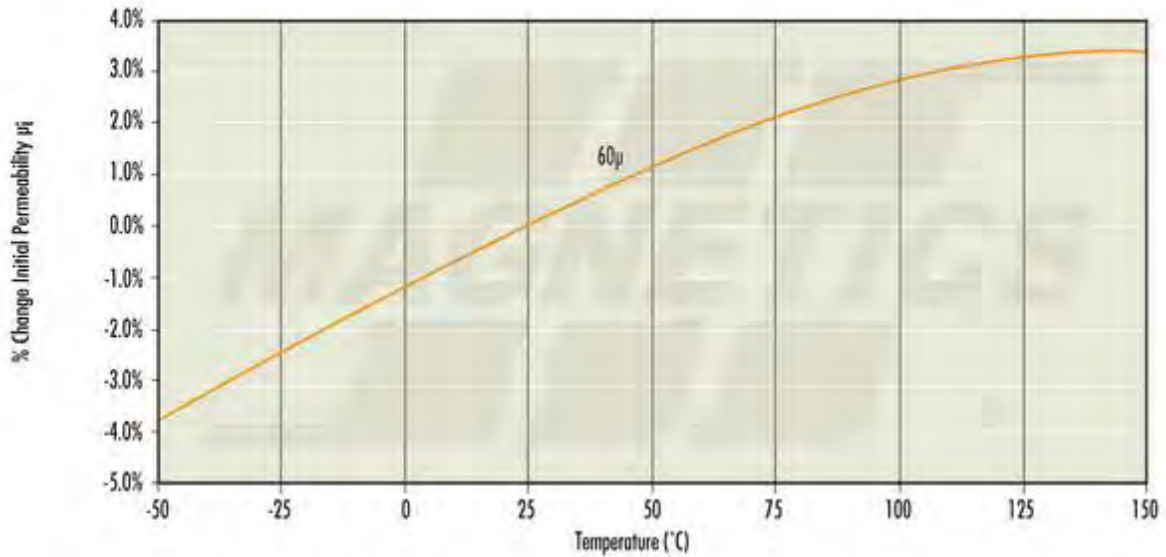


Figure 1. Permeability (hence inductance) changes no more than several percent, even at temperatures up to 200° C.

Even though the magnetic alloys used in the powder cores show greater changes in permeability with temperature, the effective permeability of the material is dramatically stabilized by the presence of the distributed gap. The permeability in the gap, of course, is unity, no matter what the temperature is. Consequently, the lowest permeability cores, having the largest effective gaps, exhibit the most temperature stability. This effect is demonstrated in Figure 2 for five varieties of Kool M μ .

Permeability versus Temperature Curves Kool M μ [®]

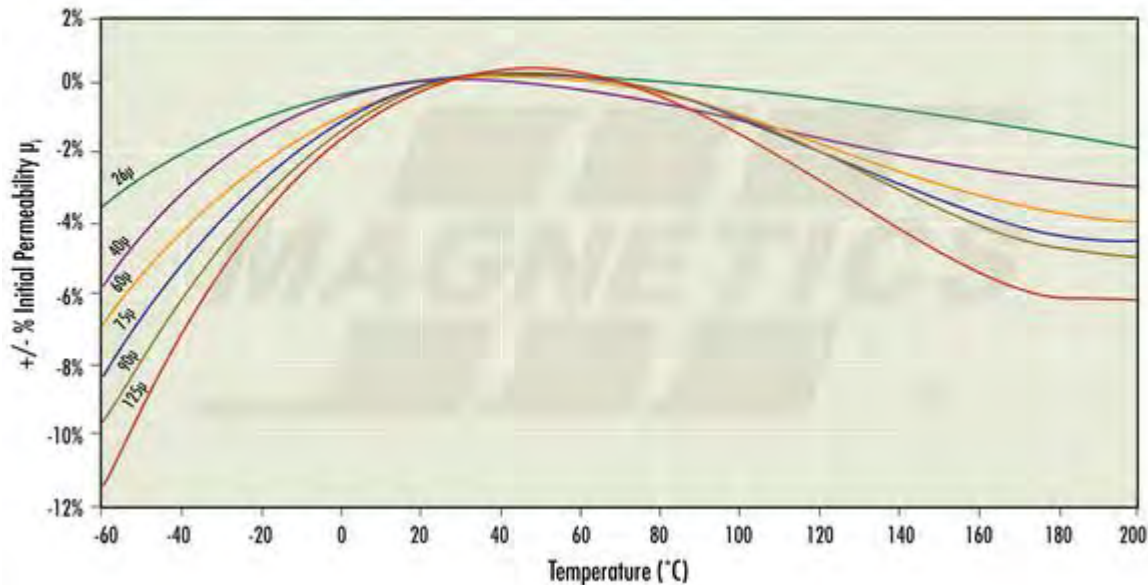


Figure 2. The lower the effective permeability of a gapped core, the less the permeability changes with temperature.

Stabilized Cores

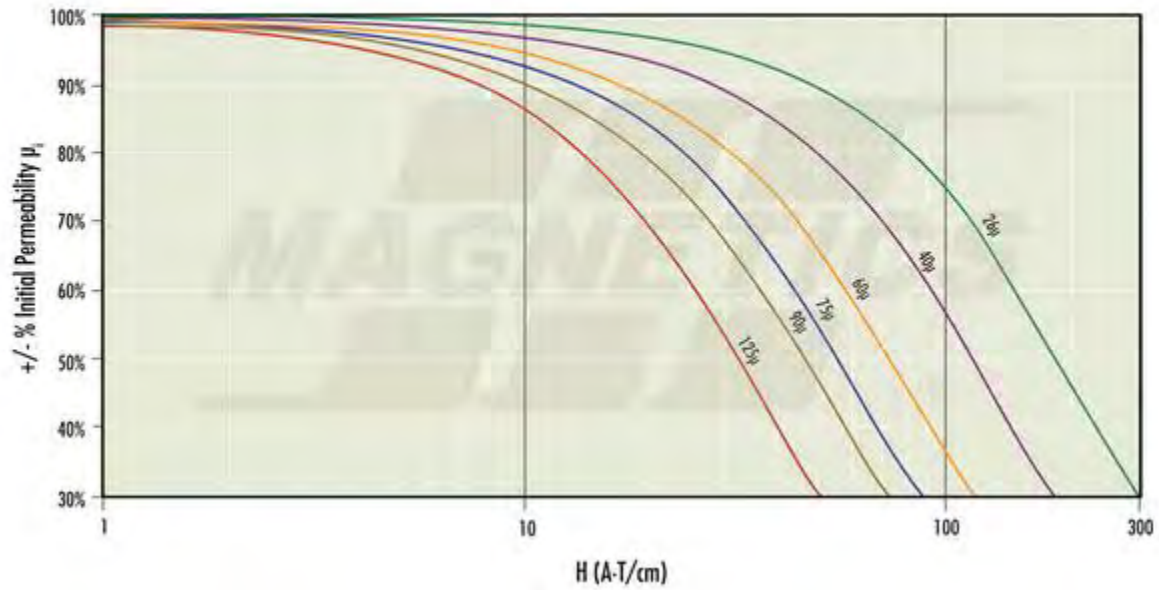
MPP cores may be provided in temperature stabilized formulations. As noted above, MPP permeability vs. temperature is quite flat and predictable. Yet there is an additional degree of control possible, and this is seen in the stabilized MPP cores. MAGNETICS achieves this special performance through precise adjustments to compensating elements in the molypermalloy chemistry. The W4, M4 and L6 stabilized core types are described in the Powder Core catalog. For example, - M4 stabilized cores are guaranteed to hold inductance within $\pm 0.25\%$ from -65°C to $+125^\circ\text{C}$. (The regular “-A2” core type is often described as “unstabilized,” which can be misleading, because it is not unstable at all.)

It is important to note that stabilization is only effective at low drive levels ($<100\text{G}$). In power inductors, stabilized cores have no advantage over standard A2 cores. Stabilized MPP cores are typically used in precision tuned filters that need an extremely low (or very linear) inductance shift over a wide temperature range. Kool M μ , High Flux, XFLUX and AmoFlux cores are not provided in stabilized form, because they are not usually the best choice in such applications.

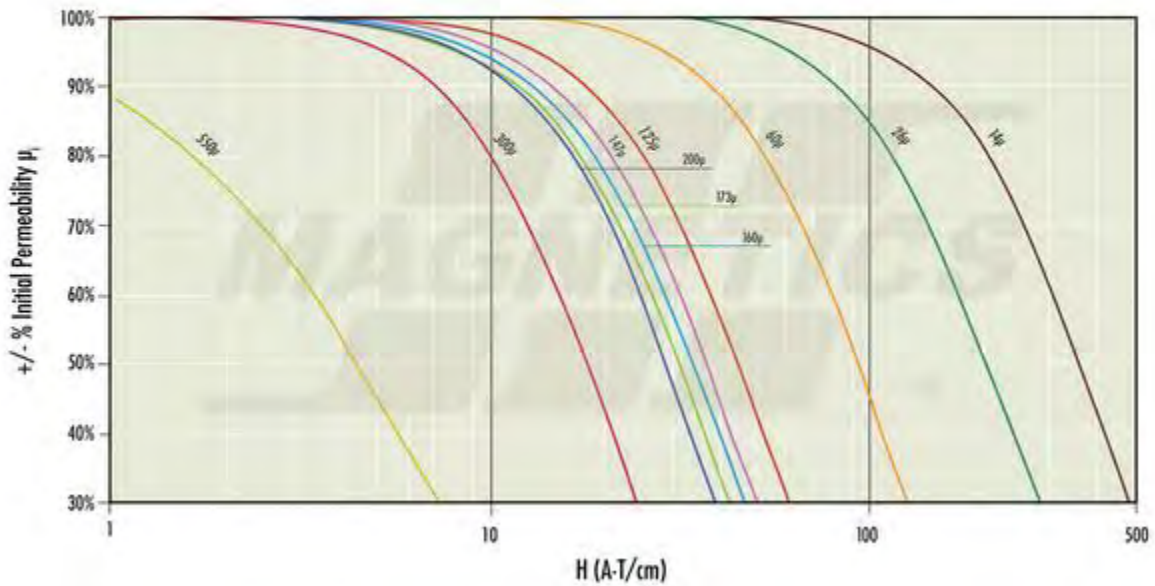
Permeability vs. DC Bias

Powder cores exhibit soft saturation. Due to the gap distributed microscopically through the material, powder cores do not reach saturation flux density (B_{sat}) all at once. Permeability rolls off, gradually and predictably losing its value at higher and higher magnetizing levels.

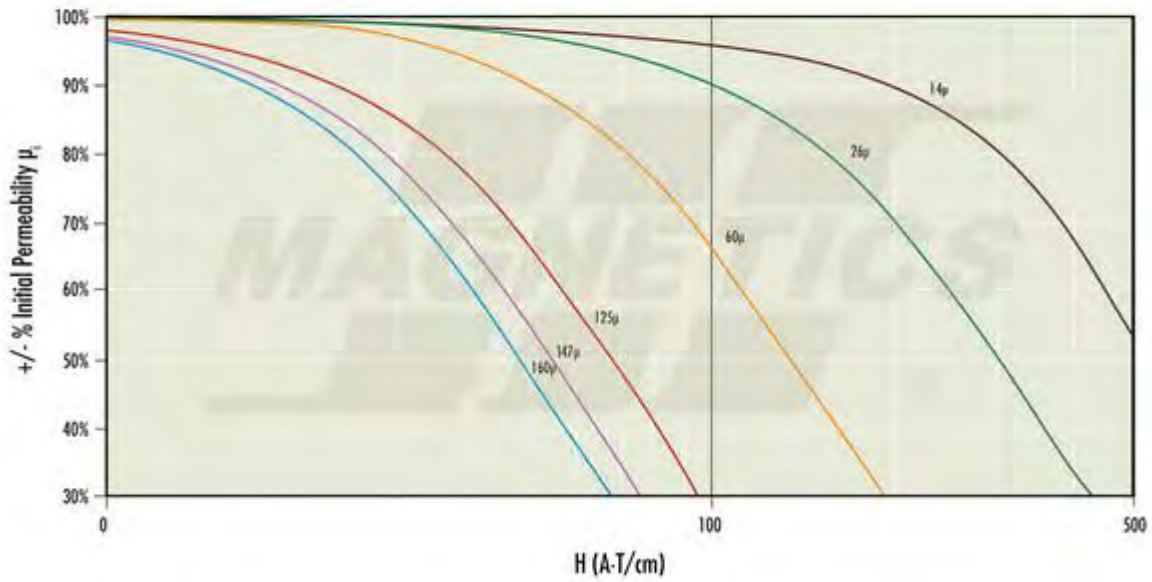
Permeability versus DC Bias Curves Kool M μ [®]



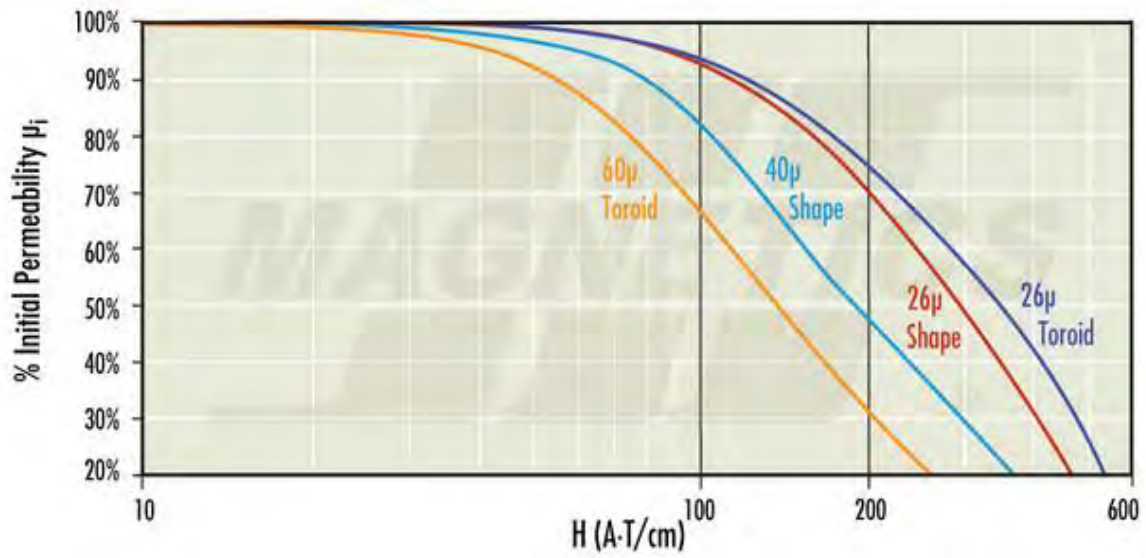
Permeability versus DC Bias Curves MPP



Permeability versus DC Bias Curves High Flux



XFlux[®] Permeability vs. DC Bias



AmoFlux DC Bias

$$(\mu/\mu_i) = 0.9931 + 2.295E-03 H + -1.291E-04 H^2 + 7.653E-07 H^3 + -1.361E-09 H^4$$

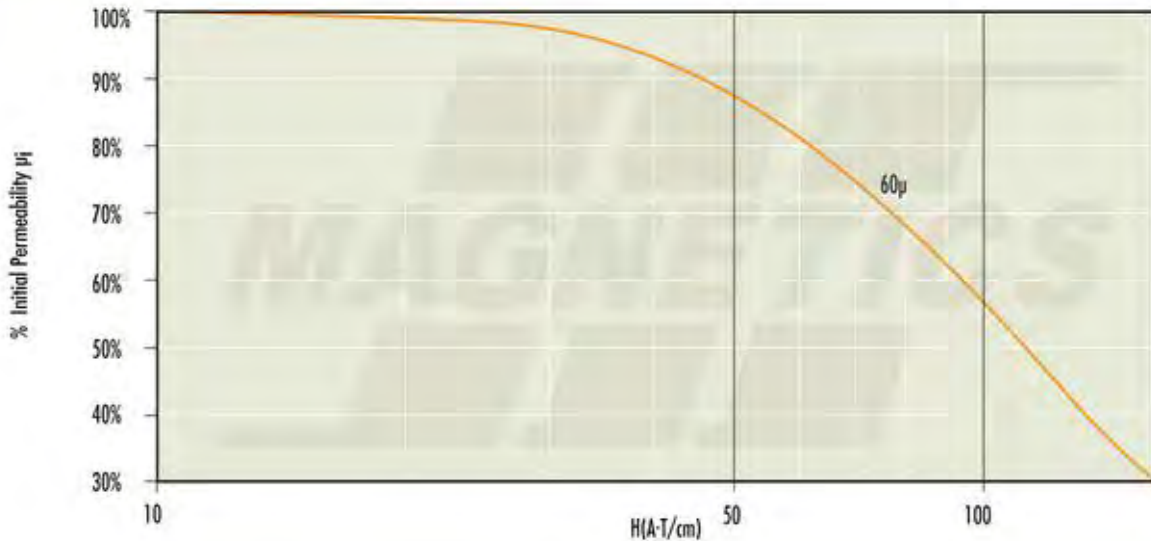


Figure 3. Permeability vs. DC Bias graphs for powder core materials.

Material	Alloy Composition	Saturation Flux Density (Tesla)	Curie Temperature	Operating Temperature Range	60μ μ flat to...
Kool Mμ	Fe Si Al	1.0	500° C	-55° C to 200° C	900 kHz
MPP	Fe Ni Mo	0.75	460° C	-55° C to 200° C	2 MHz
High Flux	Fe Ni	1.5	500° C	-55° C to 200° C	1 MHz
XFlux	Fe Si	1.6	700° C	-55° C to 200° C	500 kHz
AmoFlux	Fe Si B	1.5	400° C	-55° C to 155° C	2 MHz

Table 1. Powder Core Materials Comparison

The saturation characteristic shown by powder cores varies by only a couple of percent, even across quite wide temperature ranges. Figure 3 plots permeability vs. DC bias for all Powder Core materials. The reduction in saturation flux density with increasing temperature is not nearly as severe for the powder core alloys as for ferrites. The Curie temperatures are much higher, so typical electronics operating temperatures are well below the levels at which B_{sat} in the alloy begins to roll off significantly.

Thermal Shock

Unlike ferrites, powder cores are resistant to thermal shock. They routinely pass the most stringent military and aerospace thermal shock testing of electronic components. Although uncommon, one possible way in which a toroidal powder core may crack due to thermal effects is for the window to be wound so full of wire that the expansion of the copper with heat puts a greater tensile strain on the core than it can support. This is rare, partly because it is not natural for an economical winding process to result in such a full window.

Temperature Ratings

As noted above, Kool M μ , MPP, High Flux and XFLUX are normally rated for continuous operation up to 200°C, and AmoFlux up to 155°C, both are temperatures that are quite adequate for nearly all power electronics applications. After pressing, the Kool M μ , MPP, High Flux and XFLUX cores are given a stress-relief anneal for several hours at temperatures above 500°C. It is after this anneal that an epoxy paint is applied for dielectric protection and extra physical strength. So there is no doubt that 200°C has no damaging effects on the cores, even if applied continuously.

Inductors wound on powder cores can withstand soldering operations that exceed 200°C, if care is taken in the design of the process to reasonably protect the coating. Certain applications even use potted inductors with Kool M μ , MPP, or High Flux at temperatures greater than 200°C. This is possible because the magnetic material itself is not damaged or aged, even when operated at temperatures that are too high for the coating. The Curie temperature is 500°C for Kool M μ ; 460°C for MPP; 500°C for High Flux; 700°C for XFLUX and 400°C for AmoFlux. Some small powder cores are coated with Parylene C, an organic conformal material. This is the “-AY” coating. The maximum rating for Parylene is typically 130°C. Again, if care is taken in setting up the process, inductors using the AY coating may be exposed to soldering temperatures in excess of 130°C.

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Core Loss and Temperature Rise

The more AC current or ripple current that an inductor sees, the more significant the core losses will be. DC current, of course, does not contribute to core loss, only copper loss. The loss curves for powder core materials are not significantly affected by the DC bias operating point, since the hysteresis loops are so dramatically flattened by the distributed gap.

Naturally, losses are seen as heat, which results in temperature rise. The designer's task is to pick the optimum powder core material for his or her application, including consideration of the core losses. All other things being equal, at typical power frequencies, MPP shows the best losses, followed by Kool M μ , AmoFlux, High Flux, XFLUX, and iron powder.

The powder core catalog contains graphs of core losses, as well as equations for those curves. The losses are given as a function of frequency and flux density for the various permeabilities of each material. Losses do not vary significantly with temperature (which is not the case for ferrites.) Calculating temperature rise is discussed in the section on ferrites below.

Since iron powder is lossier than the other materials, an inductor will tend to run hotter with an iron powder core than with a similar sized, similar permeability MPP, Kool M μ , AmoFlux, High Flux or XFLUX core. The iron powder manufacturers provide curves and design notes that help the designer to set operating conditions that allow for thermal aging effects. Again, MPP, Kool M μ , AmoFlux, High Flux and XFLUX powder cores do not contain an organic binder, and they are not susceptible to aging effects.

Kool M μ E-Cores, U-Cores, Segments & Blocks

Because of the high compaction forces needed to press the alloys without a binder, MAGNETICS powder cores traditionally were manufactured only in toroids. More recently, MAGNETICS offers Kool M μ in E-core, U-core, Segment and Block form.

The high temperature properties of Kool M μ are the same whether in toroid or other shapes. This includes a slight decrease in inductance at higher temperatures; no aging effect at elevated operating temperatures; and only a small shift in the permeability vs. DC bias characteristic with temperature. And since there is no coating, E-Cores could be qualified for use at much higher temperatures.

FERRITE CORE TEMPERATURE PROPERTIES

MAGNETICS produces a complete line of Manganese-Zinc (Mn-Zn) ferrites. There is a broad selection of both materials and shapes. Toroids are available with several coating options, and shapes are available in a wide range of gap configurations.

Mn-Zn ferrites are dense, homogeneous ceramic structures made by mixing iron oxide (Fe_2O_3) with oxides or carbonates of one or more metals such as manganese, zinc, nickel, or magnesium. The oxides are precisely blended with a binder into powder. The powder is pressed into a variety of shapes, and the resulting parts are sintered in kilns at around 1000°C . Firing drives off the binder, and the result is a magnetic, ceramic material that is useful in a variety of applications. The fired parts are then machined or coated as needed.

Two distinctions should be made:

- Ferrites are ceramics, not metal alloys. Powder cores and tape wound cores are examples of alloys.
- Nickel-Zinc ferrites often used in EMI suppression are different from the Mn-Zn ferrites made by MAGNETICS and described here. (Mn-Zn ferrite also has many EMI suppression applications.) MAGNETICS ferrite materials mainly fall into one of three families:

Power Materials (L, R, P, F and T) are engineered for low core losses, allowing designers to minimize size and temperature rise, and to maximize efficiency. These materials are typically used in transformers and power inductors from 20kHz to 3Mhz. Core losses are minimized at different temperatures. L material exhibits the lowest losses at frequencies over 500 kHz.

High Permeability Materials (J and W) are engineered for: (1) high permeability and impedance over frequency and (2) low loss factor. The initial permeabilities are 5000 (**J**), and 10,000 (**W**). These materials are typically used in broadband transformers and common mode inductors, and they exhibit little or no reduction in permeability as the temperature increases from 25°C .

Low Level Materials (C, E and V) are engineered for low loss factors and for characteristic temperature factors for use at low drive levels, such as in filter inductors. (Temperature factor is a function of the shift in permeability with temperature.) In addition to filters, they are used in many specialty applications.

Ferrites do not have a practical maximum rating for temperature, but the designer needs to be aware of their characteristics. Technically, the absolute maximum temperature rating of a ferrite is its sintering temperature, the point at which the ceramic material becomes reactive with oxygen. This is generally in the vicinity of 700°C to 900°C .

Ferrites can be the best choice for high temperature applications, but it is necessary to take into account several factors: Curie point; thermal shock; limitations of coatings and bobbins; and the shift (over temperature) of losses, permeability and saturation.

Curie Temperature

Each ferrite material has a characteristic Curie temperature. The permeability is at its maximum just below this point. Above Curie temperature, the core permeability sharply disappears, and the material is no longer magnetic while it is above TC.

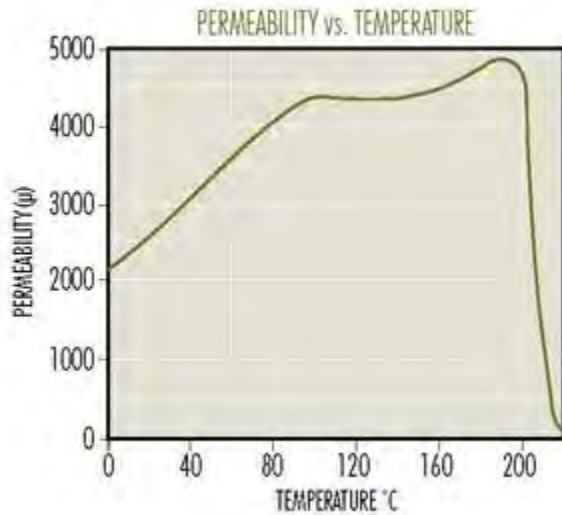


Figure 4. R material Curie temperature is 210°C

The Curie temperature is predictable for each material, and every core will be close to the published value.

TABLE 2. FERRITE CURIE TEMPERATURES

Material	T _c
R	210°C
P	210°C
F	210°C
T	220°C
L	300°C

Material	T _c
C	200°C
E	160°C
V	170°C
J	145°C
W	135°C

Ferrites are not damaged by exceeding the Curie point, even if done repeatedly or for extended periods. The magnetic properties return, unchanged, when the core cools down.

Similarly, ferrites show no aging effects or material degradation due to prolonged high temperature operation. The ceramic material is thermally stable. The change at the Curie point is in magnetic properties, not physical structure.

Thermal Shock

Because they are ceramic, ferrites can easily crack if exposed to rapid changes in temperature (thermal shock.) The material becomes vulnerable when it is changed by 4°C to 8°C or more per minute. An increase or decrease of 2°C or 3°C per minute is generally safe.

Ferrites are poor thermal conductors, which is a benefit in relation to thermal shock. A short exposure to high temperature (such as a soldering operation) is often too brief to cause core heating or cracking. Likewise, after cores have been assembled into wound units, and possibly taped, varnished, potted and attached to other components, the thermal shock seen *by the core* can be quite different from the nominal changes in temperature due to manufacturing, testing or operation. Testing of prototypes is essential whenever there is a possibility of thermal shock to the core.

Three common ways that thermal shock can crack ferrites are:

- (1) Sudden quenching to room temperature after a baking or curing operation.
- (2) Grinding the cores without adequate lubrication. (Grinding makes a lot of heat, all applied at a single point. Generous amounts of water should be used.)
- (3) Thermal shock testing of a bare wound core.

Coatings

Ferrite toroids are available in three standard coatings, **V**, **Z** and **Y**. All present a smooth winding surface. **Z** and **Y** provide dielectric isolation and a second layer of insulation after the magnet wire varnish.

V coating (Nylon) is thicker than epoxy and can stand temperatures up to 155°C. Nylon finishes are generally applied to cores ranging in O.D. (outside diameter) from 12.7 mm to 29 mm.

Z coating (Epoxy) is rated at 200°C. Very large and very small cores are coated with an epoxy finish.

The voltage breakdown guarantee of nylon and epoxy coating is 1000 volts wire to wire. Nylon cushions better and is more resistant to solvents. Both finishes are held to the same electrical specifications.

Y coating (Parylene C[®]) is a vacuum deposited coating providing good resistance to moisture and organic solvents. Electrical characteristics are superior to other coatings. It is offered on small toroids and rated to 130°C for continuous operation. Parylene can be exposed for brief periods to soldering temperatures up to 200°C.

Bobbins and Headers

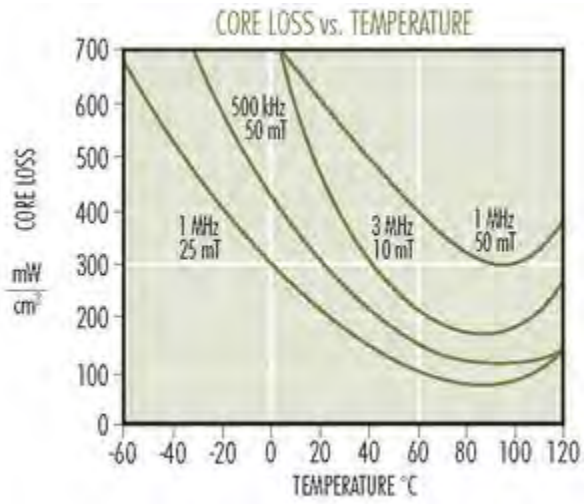
Various plastics are used in the ferrite hardware. The MAGNETICS ferrite catalog lists the materials used in bobbin and toroid mounts. Temperature and flammability data is also included.

Loss vs. Temperature

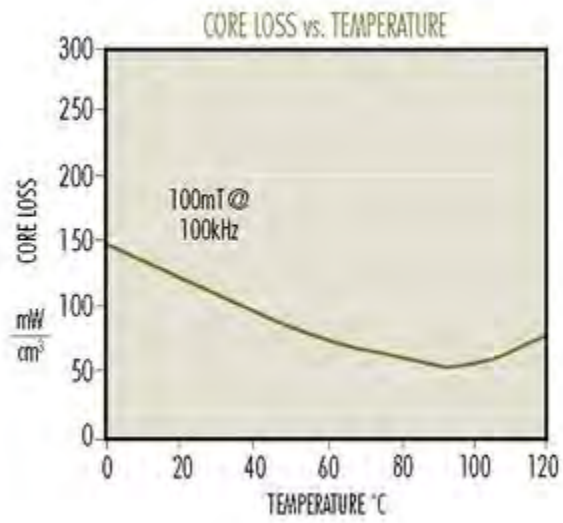
Power materials are engineered to have characteristic core loss curves over temperature. When the loss minimum is at an elevated temperature, designers can make transformers and inductors that are smaller and more efficient, stabilizing at lower temperatures.

Core Loss vs. Temperature

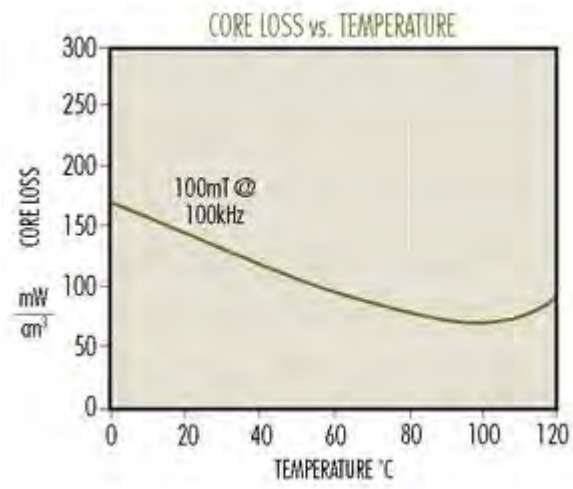
L Material



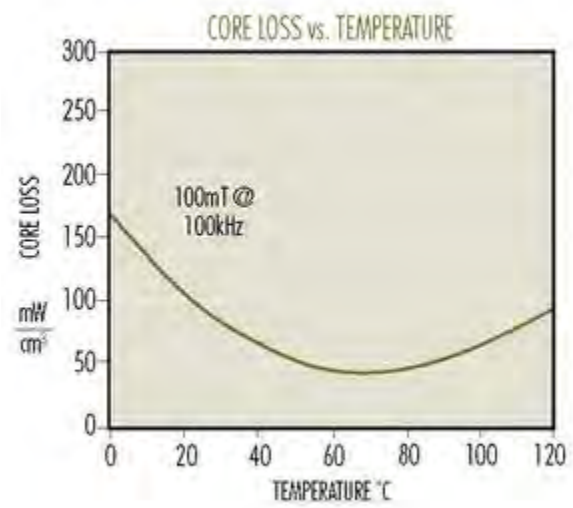
R Material



P Material



F Material



T Material

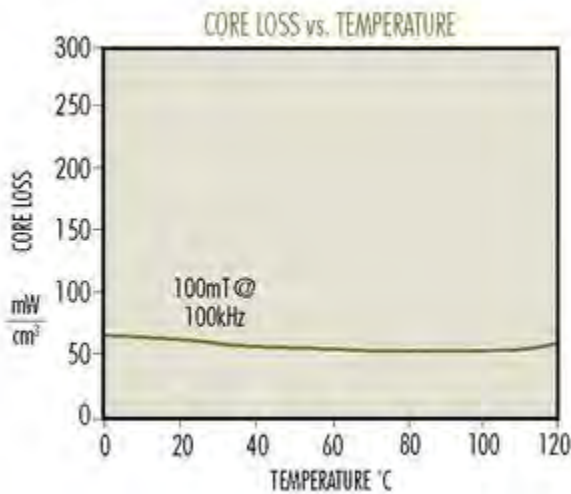


Figure 5. *P material has its lowest losses at 90°C to 110°C. R material, at 80°C to 100°C. F and T materials have their lowest losses at 60°C -80 °C and 60°C -100°C respectively.*

Transformers or inductors that are designed to operate beyond the material's core loss minimum are vulnerable to thermal runaway. As the core heats, it becomes less efficient, resulting in even more heating. Only when the device is so hot that the emitted energy catches up with the escalating loss energy, does it stabilize.

The observed temperature rise depends heavily on environmental factors such as ambient temperature, airflow, geometry, and the thermal conductivity of all the materials involved. A useful first cut equation relates the surface area of the magnetic with the total losses to yield an approximate temperature rise (from room temperature, in still air):

$$\text{Rise (}^\circ\text{C)} = [\text{Total Loss (mW)} / \text{Surf. Area (cm}^2)]^{0.833}$$

For example, assume a transformer with copper and core adding up to about 0.6 W, and having a surface area (top, sides and bottom of the wound device) around 15 cm². Then the approximate ΔT is $[600/15]^{0.833} = 22^\circ\text{C}$.

Other factors that should not be overlooked are skin and proximity effects in the copper conductors, and fringing effects. The fringing problem occurs with gapped cores, where flux at the gap can intersect with copper near the gap and generate eddy currents. It is possible for the losses due to those eddy currents to exceed the total core losses in the inductor.

Ferrite material selection is also frequency-dependent. For example, R, P, and F materials are useful across a wide range of frequencies, even into the MHz, while L material has superior losses at high frequencies (500 kHz to 3 MHz.)

Permeability vs. Temperature

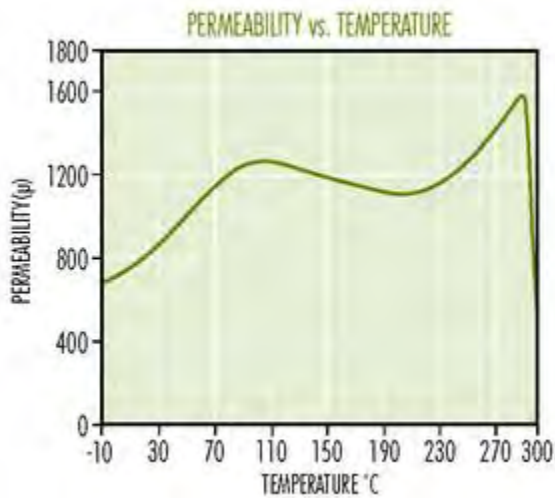
In all ferrites, permeability is sensitive to temperature. The temperature-dependency of permeability is predictable for each material, and it can be used to the designer's advantage. (Of course, permeability is sensitive to other factors as well, especially flux density. Consult the ferrite catalog for data on the shift in permeability with flux density.)

As already noted, there is a primary peak in permeability that occurs just below the Curie temperature. There is typically a secondary peak that is seen at a lower temperature, characteristic for each material, and with greater or lesser amplitude.

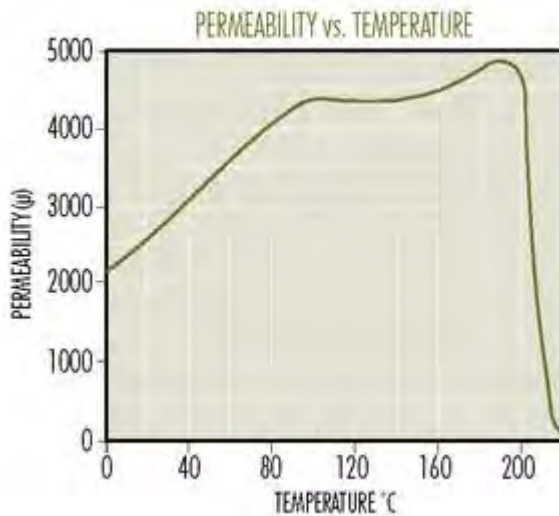
In typical power materials, the permeability is not a critical factor. Inductance relates to exciting current, and so long as a reasonable primary inductance is achieved, changes in inductance with temperature or drive are much less significant than changes in loss characteristics. There is a loose correlation between the shape of the permeability vs. temperature curve and the permeability vs. core loss curve. (Compare with *Core Loss vs. Temperature* curves)

Permeability vs. Temperature

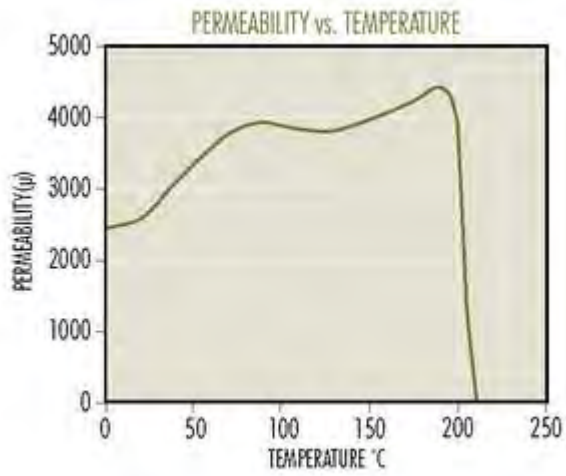
L Material



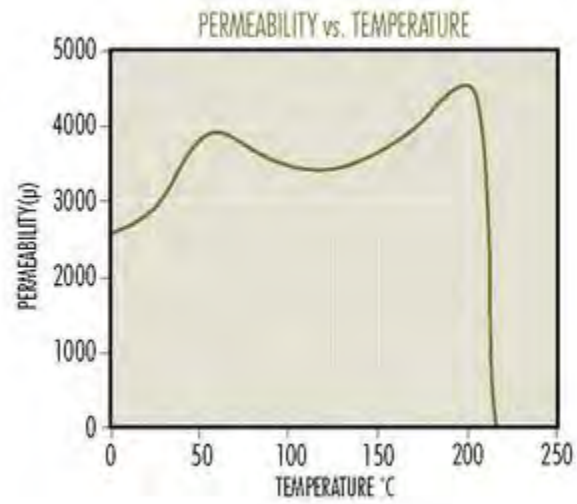
R Material



P Material



F Material



T Material

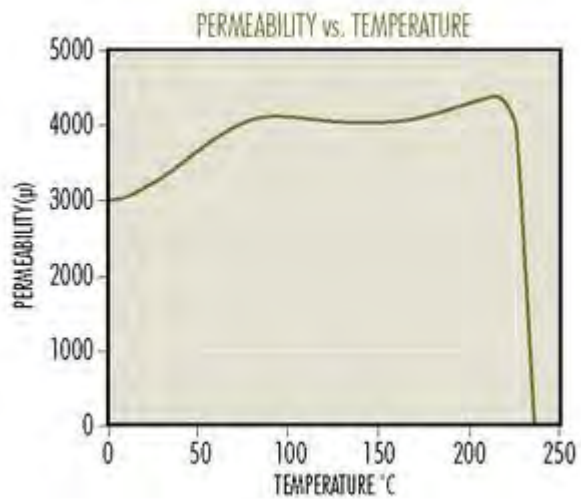
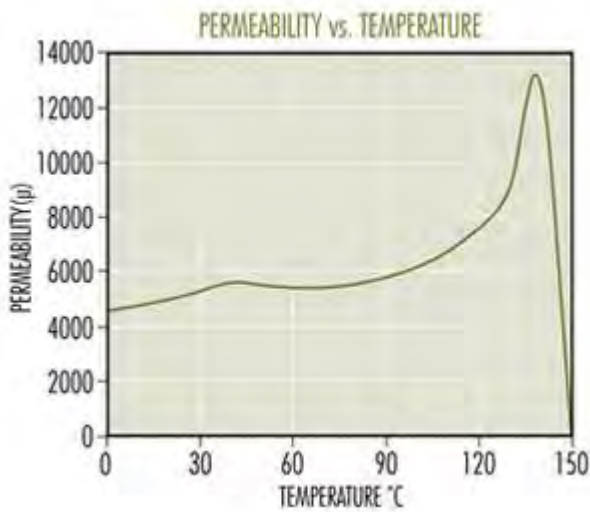


Figure 6. Power materials are typically used at flux levels and temperatures that increase the permeability. These curves are taken at 1000 Gauss (0.1 T) drive.

For high permeability ferrites, the permeability change with temperature is much more significant. The natural tendency for high permeability materials is to exhibit a saddle shape, or a minimum value, typically between room temperature and 75°C or 100°C. This is undesirable, since a designer does not wish to see, for example, decreased impedance if his or her common mode choke heats up. MAGNETICS cores are engineered to eliminate the saddle shape, so that the permeability is nearly flat or increasing with increasing temperature. (Figure 7.)

J Material



W Material

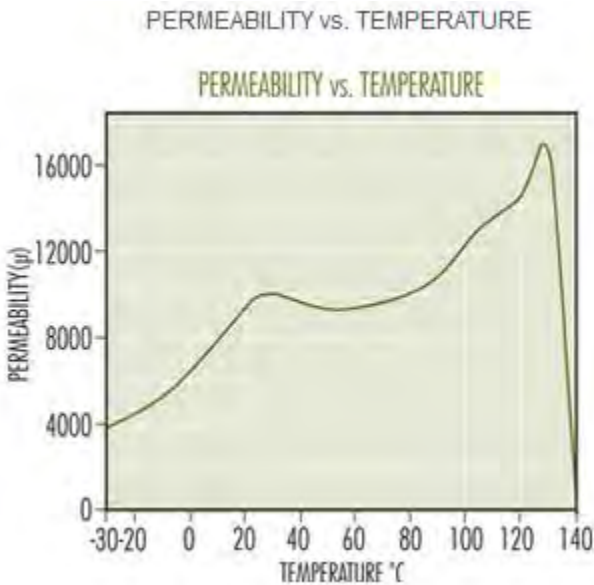


Figure 7. MAGNETICS high permeability materials exhibit nearly flat or positive shift in permeability with temperature.

In gapped cores, the measured μ_e vs. temperature curve is greatly flattened. The air gap results in an effective permeability (μ_e) for the core that is much lower than the bulk material permeability. (The same effect is seen in distributed gap powder cores.) The gap permeability is constant over temperature (unity), and therefore the combined effective permeability is much closer to a constant value. The deeper the gap, the more the gap dominates, and the flatter the μ_e vs. temperature curve will be. (Figure 8.)

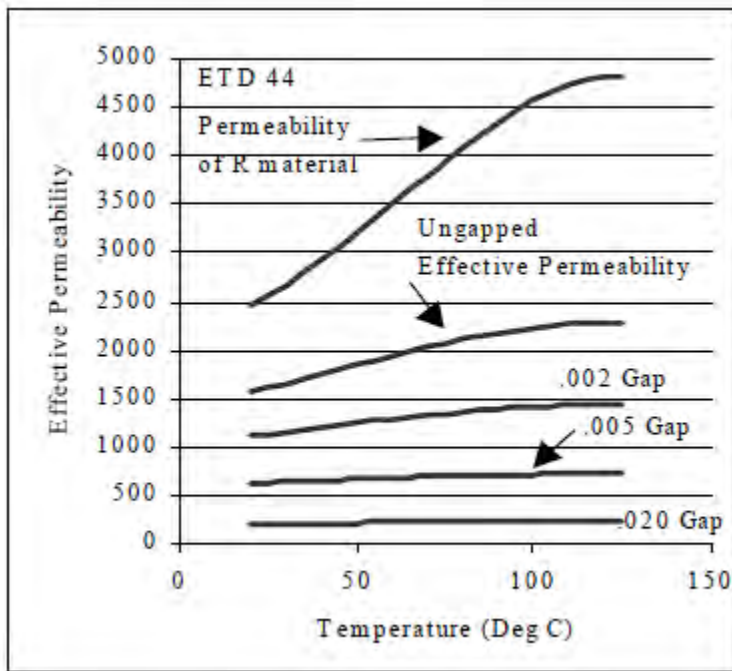
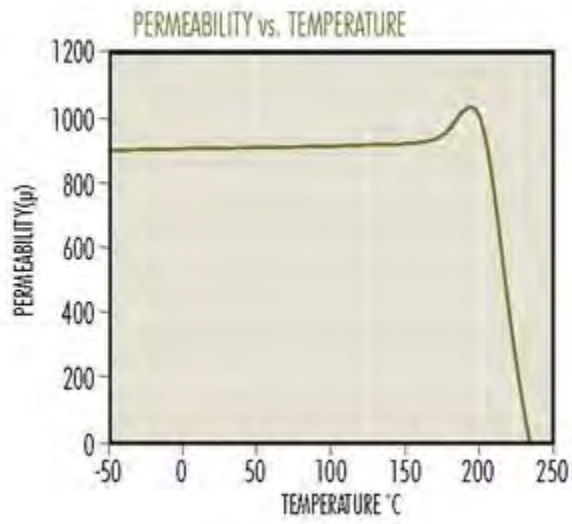


Figure 8. The deeper the gap, the more the μ_e vs. temp. curve is flattened. Even an ungapped core set has enough air at the mating surface to flatten the curve significantly.

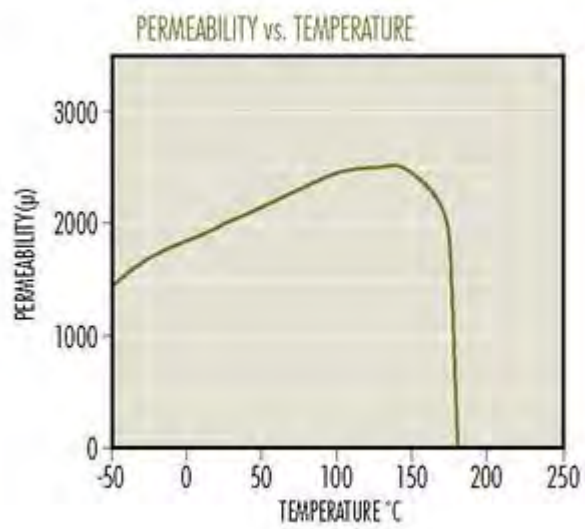
Some applications, such as filter inductors, require very flat or linear inductance over temperature. Often powder cores are the best solution, but ferrites are also used. Linear ferrites are produced with tightly controlled permeability vs. temperature characteristics. These are then made into cores, typically pot cores, and a gap is selected for the core. The gap value is chosen to balance the requirement for a certain minimum inductance against the need to sufficiently flatten the effective permeability curve.

Linear ferrite designs are controlled by specifying the temperature factor (T_F) or the effective temperature coefficient (T_{Ce}). T_F is a measure of the ppm shift in material permeability per degree C. T_{Ce} is the product of the T_F and the μ_e of the gapped core, yielding a measure of the shift in the gapped core. The deeper the gap, the lower the μ_e , and therefore the lower or flatter the T_{Ce} .

C Material



E Material



V Material

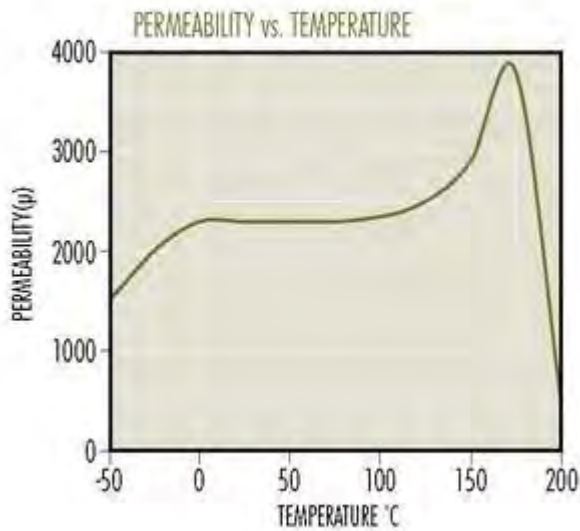


Figure 9. The low level materials are engineered for filter applications. V is quite flat in the 20°C to 80°C range. C is fairly flat in a wider temperature range. E is linear, with a temperature factor (T_F) to match that of some capacitors. See the ferrite catalog for T_F data and design notes.

Saturation vs. Temperature

In all ferrites, saturation flux density (B_{sat}) declines as the temperature goes up. In many applications, to keep the losses low, cores are not operated near saturation. But the designer needs to verify that the reduction in B_{sat} at elevated temperature will not interfere with the operation of the device.

Figure 10 shows the flux density characteristic of a high temperature power material. In practice it would be unusual for a transformer to approach the saturation values shown, especially at frequencies above 30 or 40 KHz. At typical switching frequencies, transformers are designed for flux densities that result in maximum desired core loss. The designer sets the flux density (B) low enough for tolerable losses, but high enough to use a suitably small core. If a good power ferrite is used, the resulting B level is well below saturation, even at very high temperatures. Good power ferrites exhibit high Curie temperatures and high B_{sat} at temperature, in addition to their low losses and their elevated minimum loss temperatures.

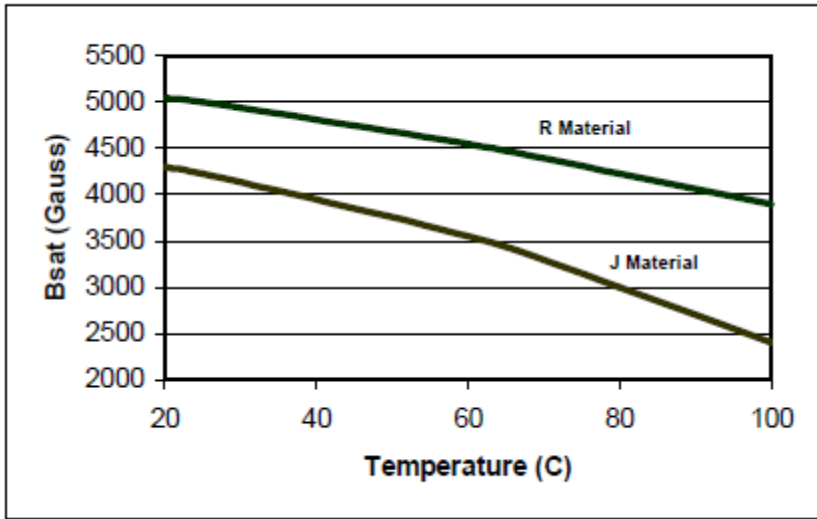


Figure 10. *Bsat vs. temperature for a power ferrite (R) and a high permeability ferrite (J).*

Ferrite cores are used in inductors by employing a discrete gap, created by grinding down on the center leg or by separating the core halves with spacers. The gapped core will store a certain amount of energy, depending on the depth of the gap, the size of the core, and the material saturation. Figure 11 illustrates the saturation effect in inductors. MAGNETICS' μ_e vs. H curve is used to verify that an inductor will not saturate at maximum current.

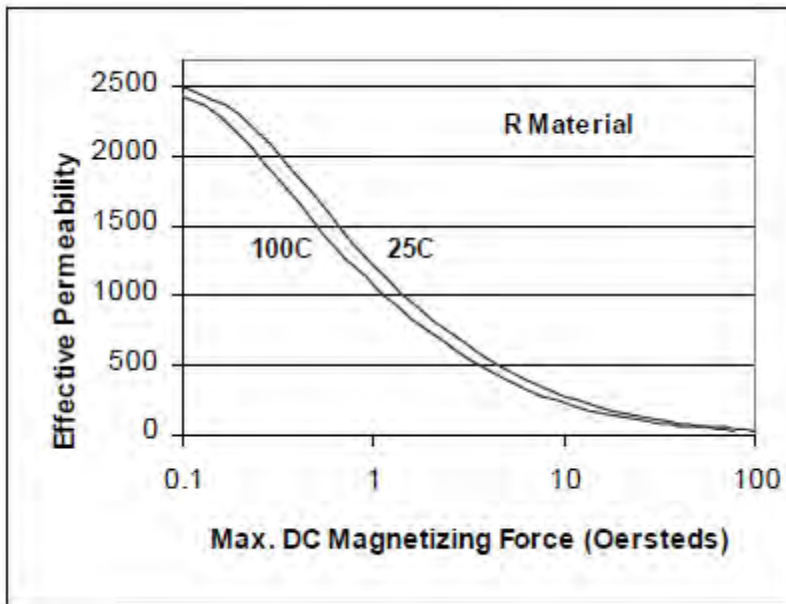


Figure 11. *Maximum DC Bias for gapped ferrite cores.*

Due to the discrete gap in a ferrite inductor, saturation with bias must be considered differently than with a powder core. The powder core distributed gap results in soft saturation, which means predictable, steady roll-off. In contrast, ferrite saturation is sharp, and the designer must take care to stay below the saturation point, hence the "Maximum DC Bias" parameter given in Figure 11.

For an inductor that will operate at elevated temperature, the maximum bias level is derated by the same percentage that the B_{sat} for the material decreases for that temperature. For example, comparing Figure 10 with Figure 11, it can be seen that R material shifts 22% from 25 °C to 100 °C. The saturation decreases by 22%, and therefore the maximum H level is derated by the same amount.

TAPE WOUND CORE TEMPERATURE PROPERTIES

One of the primary advantages of toroidal tape wound cores is that they can operate in extreme environments, including extreme temperatures. Tape wound cores are often found in applications where ruggedness and small size are at a premium: aerospace, military, harsh industrial processes, and petroleum drilling.

In most cases, the tape core maximum continuous operating temperature is limited by the case or coating. Cores are placed in cases in order to protect the strain-sensitive magnetic material from physical stresses. Also, coatings and cases serve to prevent windings from being damaged by the sharp corners on bare cores. Temperature ratings by material and case are summarized in Table 3 below. See the MAGNETICS' Strip Wound Cores catalog for additional information.

Tape core alloys are not damaged or aged by high temperatures. Typical temperature ratings for cases, coatings, wire and other components are far below alloy temperature limitations.

Magnetic properties of tape core alloys are less sensitive to temperature than those of ferrites. The percentage shift in saturation and core loss is relatively small. For example, B_{sat} of permalloy is typically reduced 8% - 9% at 125 °C compared with 25 °C. B_{sat} for Orthonol® typically shifts 9% to 11% in the same interval.

Nevertheless, some tape core applications rely on precise, repeatable B-H loop response, and temperature compensation in the circuit may be necessary. Consult the MAGNETICS application note "Fundamentals of Tape Wound Core Design" (TWCS1) for more information.

TABLE 3. TAPE CORE TEMPERATURE RATINGS

Material	Code	Composition	Curie Temp	Maximum Continuous Operating Temperatures					
				Nylon Case	Phenolic Case	Aluminum Case	Epoxy Coated	Bare Core	Bobbin Core
Square Permalloy	D	Nickel-Iron	460°C	200°C	125°C	200°C	N.R.	N.R.	200°C
Round Permalloy	R	Nickel-Iron	460°C	200°C	125°C	200°C	N.R.	N.R.	200°C
Supermalloy	F	Nickel-Iron	460°C	200°C	125°C	200°C	N.R.	N.R.	200°C
Orthonol	A	Nickel-Iron	500°C	200°C	125°C	200°C	N.R.	N.R.	200°C
48 Alloy	H	Nickel-Iron	500°C	200°C	125°C	200°C	N.R.	N.R.	200°C
Magnesil	K	Iron-Silicon	750°C	200°C	125°C	200°C	125°C	500°C	N.A.
Supermendur	S	Cobalt-Iron	940°C	200°C	125°C	200°C	N.R.	N.R.	N.A.

N.A.-Not Available N.R.-Not Recommended

MAXIMUM RATED TEMPERATURES FOR MAGNETICS CORES
(For Continuous Operation)

Powder Cores

MPP	200°C
Kool Mμ	200°C
High Flux	200°C
XFLUX	200°C
AmoFlux	155°C

Ratings are set by coating. Powder Core materials can go much higher.
 For parylene coated 130°C (-AY code)

Ferrite Cores

Shapes	Curie Temp*
Uncoated Toroids	Curie Temp*
Epoxy Coated Toroids	200°C
Nylon Coated Toroids	155°C
Parylene Coated Toroids	130°C

*Ferrites lose their magnetic properties while above the Curie temperature, but are not damaged. Effect is completely reversible.

Tape Wound Toroids

Material	Nylon Case	Phenolic Case	Aluminum Case	Epoxy Coated	Bare Core	Bobbin Core
Square Permalloy (D)	200°C	125°C	200°C	N.R.	N.R.	200°C
Round Permalloy (R)	200°C	125°C	200°C	N.R.	N.R.	200°C
Supermalloy (F)	200°C	125°C	200°C	N.R.	N.R.	200°C
Orthonol (A)	200°C	125°C	200°C	N.R.	N.R.	200°C
48 Alloy (H)	200°C	125°C	200°C	N.R.	N.R.	200°C
Magnesil (K)	200°C	125°C	200°C	125°C	500°C	N.A.
Supremendur (S)	200°C	125°C	200°C	N.R.	N.R.	N.A.

N.A.-Not Available N.R.-Not Recommended

CURIE TEMPERATURES FOR MAGNETICS MATERIALS

MPP	460°C
Kool M μ	500°C
High Flux	500°C
XFLUX	700°C
AmoFlux	400°C
P Ferrite	210°C
R Ferrite	210°C

F Ferrite	210°C
T Ferrite	220°C
L Ferrite	300°C
J Ferrite	145°C
W Ferrite	135°C
C Ferrite	200°C
E Ferrite	160°C

V Ferrite	170°C
Permalloys	460°C
Orthonol	500°C
48 Alloy	500°C
Magnesil	750°C



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