LEAKAGE FLUX CONSIDERATIONS ON
KOOL Mμ "E" CORES

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Abstract

Kool Mu, a Silicon-Aluminum-Iron powder, is a popular soft magnetic material used in switch mode power supplies. In the past Kool Mu has only been available in toroidal shaped cores, but recently Kool Mu "E" shaped cores have been developed. Kool Mu E cores are often used in place of gapped ferrite cores since Kool Mu has twice the flux capacity of ferrite, and its distributed air-gapped structure does not suffer from the gap loss concerns associated with ferrites. The leakage flux of Kool Mu E cores is significantly unlike the leakage flux of the gapped ferrite cores that they are replacing.

This paper looks at how this leakage flux impacts inductance measurement, core losses and potential circuit board layout pitfalls. Graphs will be presented showing the deviation from nominal inductance as a function of wire bobbin fill and material permeability. Since metallic clips and copper EMI shields are commonly used in transformers, data will be presented showing how common transformer accessories can change core losses. A general discussion on how the stray magnetic field could influence power supply circuit board layout will be presented

Air-gaps

Inductor and flyback transformer cores usually require an air-gap to prevent core saturation due to high current flow in the windings. A common core shape is the EE set. As shown in figure 1, this shape is typically gapped by one of three ways. The first method shows a ferrite core that has the entire air-gap on the center leg. The second method is to place the air-gap across all three legs. This is often done for prototyping purposes or to somewhat distribute the air-gap. The three leg air-gap is half the size of the center-leg air-gap, resulting in each of the two flux paths encountering the same amount of air-gap. Both methods use a discrete air-gap as opposed to the third method where a distributed air-gap is used. The distributed air-gap is comprised of a multitude of tiny air-gaps that are made by insulating the magnetic powder particles which comprise the core.
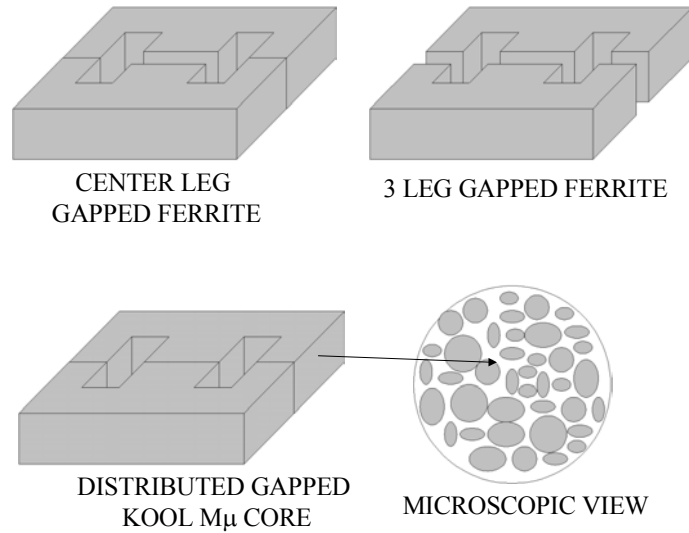
CENTER LEG
GAPPED FERRITE

3 LEG GAPPED FERRITE

DISTRIBUTED GAPPED
KOOL Mμ CORE

MICROSCOPIC VIEW

Figure 1.

As the air-gap is varied the effective permeability of the core varies. While it is obvious how the air-gap is varied for a discrete air-gap, it is worth noting that the distributed air-gap method can also have its air-gap varied. This is accomplished by changing the amount of insulation placed on the magnetic powder particles. This process does have some practical limitations which limit the variation in this distributed air-gap.
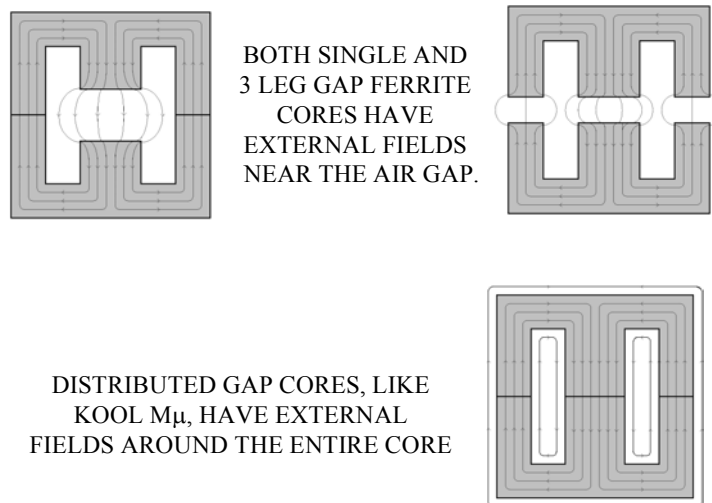

BOTH SINGLE AND
3 LEG GAP FERRITE
CORES HAVE
EXTERNAL FIELDS
NEAR THE AIR GAP.

DISTRIBUTED GAP CORES, LIKE
KOOL Mμ, HAVE EXTERNAL
FIELDS AROUND THE ENTIRE CORE

Figure 2.

The data presented in this paper used ferrite cores made of Magnetics P material which has an initial permeability of 2500. By gapping the cores, the relatively high permeability material, $\mu = 2500$, is combined with the low permeability of the air-gaps, $\mu = 1$, resulting in effective permeabilities of 26, 40, 60 and 90. The distributed air-gapped Kool Mμ cores had insulation amounts varied to yield the same effective permeabilities of 26, 40, 60 and 90.
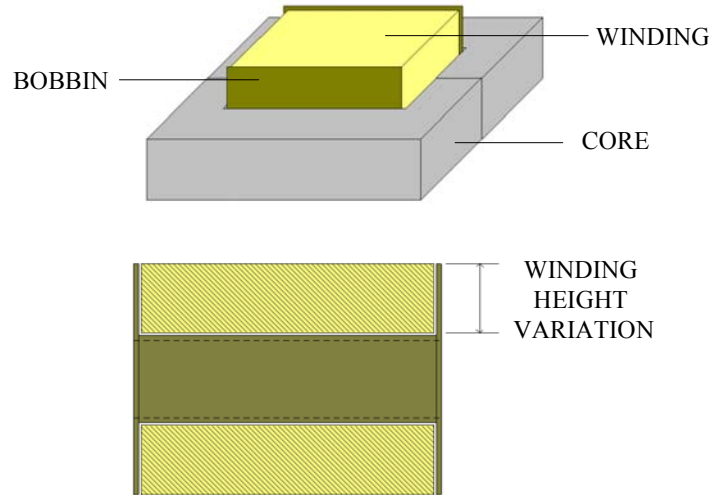
Figure 3.

Winding configuration, core shape, material permeability and other parameters all contribute to a wound magnetic component's leakage flux. To eliminate some of these variables the same core size and wound bobbins were used to obtain the data presented. Figure 2 shows a simplified two dimensional view of the leakage field for the discrete gapped ferrites and the distributed gapped Kool Mµ. The leakage field for the discrete gapped cores concentrates around the air-gaps. The leakage field for the distributed gapped cores is evenly distributed around the outside of the core structure.

Inductance Measurement Error Due to Winding Height Variation

It is common practice to denote the A_L value of a core in mH/1000 turns. A simple calculation gives the expected inductance in mH for any number of turns as follows:
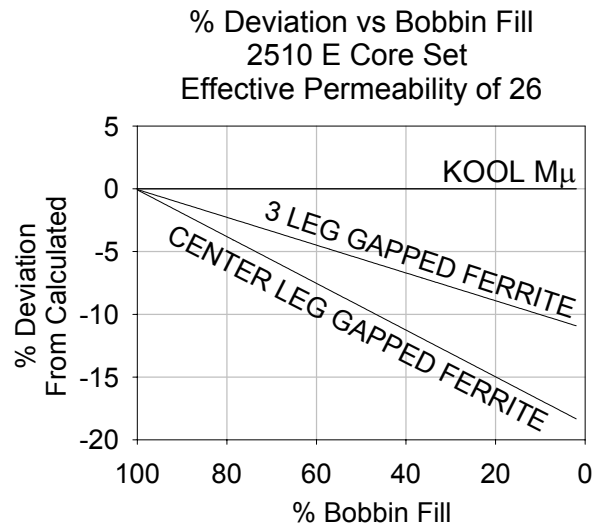
$$L = (N^2/10^6)A_L \qquad \text{(mH)}$$

Figure 4.

% Deviation vs Bobbin Fill
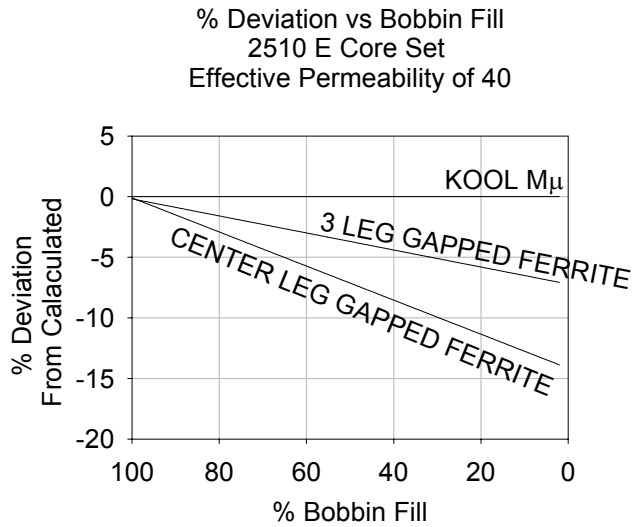2510 E Core Set
Effective Permeability of 40

Figure 5.

For ungapped ferrite cores this equation is accurate, but for gapped ferrite cores the leakage inductance can cause significant error between the calculated and measured inductance. A major source of this error is due to the amount of wire fill in the bobbin. This is indicated by the winding height variation shown in figure 3. As the winding height is decreased the amount of error for ferrite cores increases as shown in figure 4. The center leg gapped core has the greatest error followed by the three leg gapped ferrite core. Interestingly the distributed gapped Kool Mμ cores showed no appreciable error. As effective permeability is increased, the leakage flux decreases, and the error decreases as shown in figure 5 through 7.
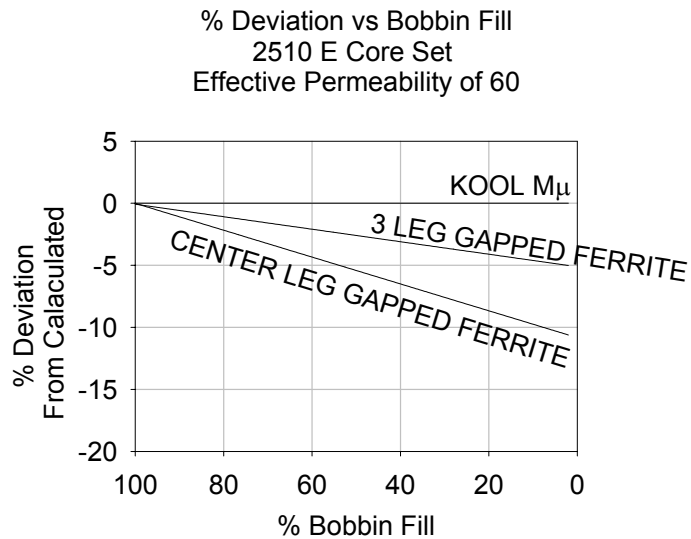
% Deviation vs Bobbin Fill
2510 E Core Set
Effective Permeability of 60

Figure 6.

% Deviation vs Bobbin Fill
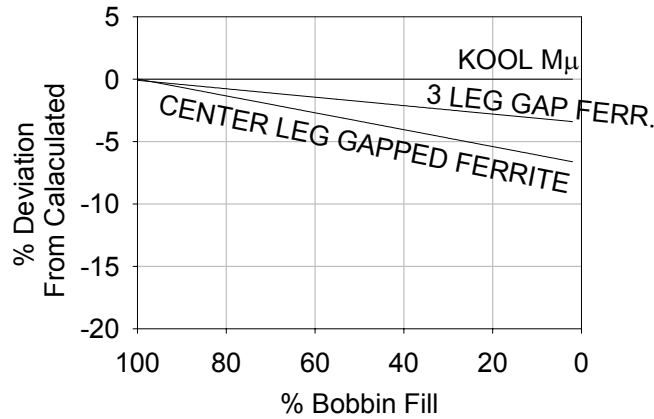2510 E Core Set
Effective Permeability of 90

Figure 7.

Inductance Measurement Error Due to Single Layer Windings

A single layer inductance measurement is often used, particularly at an incoming inspection test. On an ungapped ferrite core this should not cause significant error but, on a gapped core significant error can be encountered. Figure 8 shows how a single layer winding was varied over the entire winding height. The deviation from calculated inductance is plotted for cores with effective permeabilities of 26 and 90 in figures 9 and 10. Similar to the winding height error, this deviation is less with higher effective permeability. It is also less when the air-gap becomes more distributed, as shown with both the three leg and distributed gapped cores.
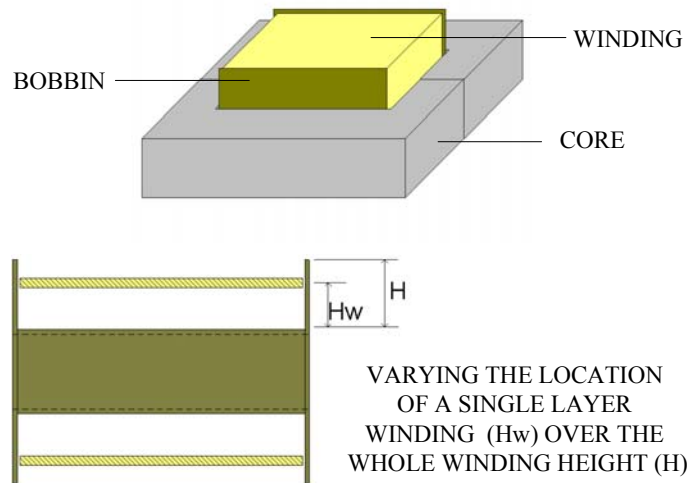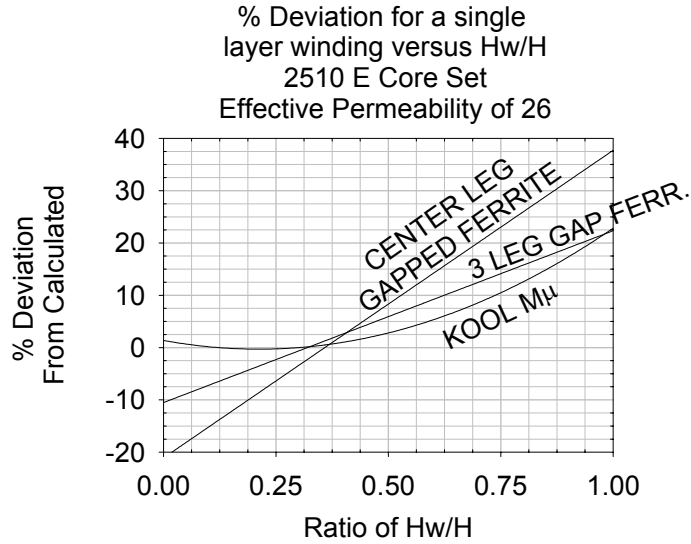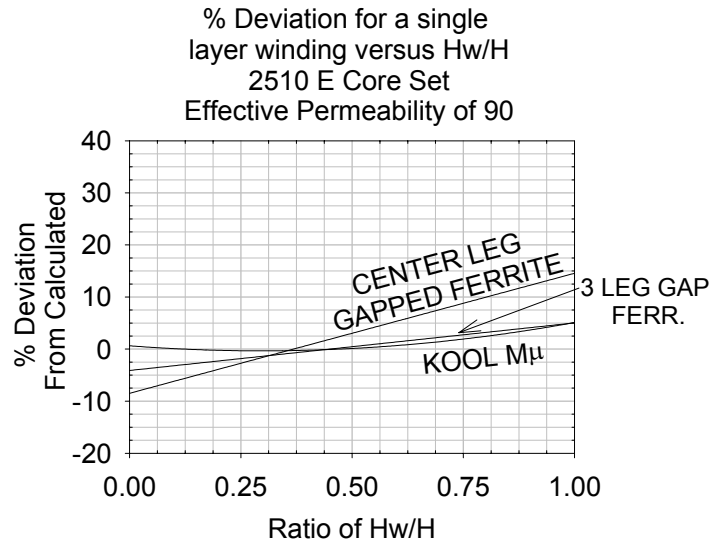

VARYING THE LOCATION
OF A SINGLE LAYER
WINDING (Hw) OVER THE
WHOLE WINDING HEIGHT (H)

Figure 8.

% Deviation for a single
layer winding versus Hw/H
2510 E Core Set
Effective Permeability of 26

Figure 9.

% Deviation for a single
layer winding versus Hw/H
2510 E Core Set
Effective Permeability of 90

Figure 10.

Core Loss Comparison

Manufacturers' ferrite core loss data is always given assuming an ungapped core, not a gapped core. Core loss on gapped ferrite cores can be dramatically higher than estimated from the catalog material curves due to gap-loss. Gap-loss can occur due to the fringing flux which bows out around the discrete air-gap, intersecting the copper windings and generating excessive eddy currents in the windings. Gap-loss is also the result of flux lines that bunch together at the corners of the core before bridging the air-gap, generating inefficient hot spots. While distributed air-gap cores like Kool Mµ have some gap-loss, it is already accounted for in the catalog core loss data.

Special winding techniques can decrease gap-loss. One common technique is to keep the first winding layer at least one gap distance from the center leg. Other approaches such as a placing a flux concentrator in the air-gap can also decrease gap-loss. The data presented here used fully wound bobbins and no attempt was made to space the winding from the air-gap.

CORE LOSS AT 1000 GAUSS
2510 E CORE SET
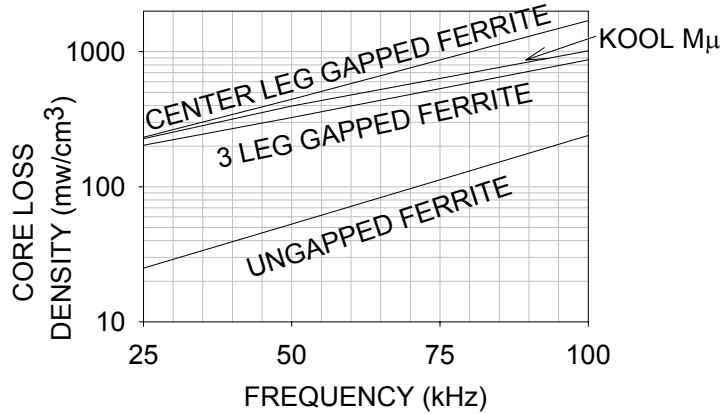EFFECTIVE PERMEABILITY OF 26

Figure 11.

In the case of figure 11, a gapped ferrite core was wound with a fully wound bobbin and found to have higher core losses than the similar Kool Mμ core. The size of this center leg air-gap was about .100". As the effective permeability is increased, the gap becomes smaller, and losses decrease as shown in figure 12, which had a center leg air-gap of about .030".

CORE LOSS AT 1000 GAUSS
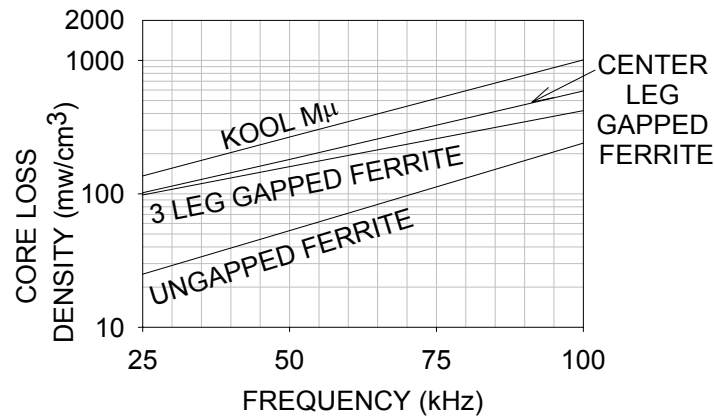2510 E CORE SET
EFFECTIVE PERMEABILITY OF 90

Figure 12.

Impact of Transformer Accessories on Core Loss

Both ferrite and Kool Mμ E cores are usually assembled by gluing the mating legs together and taping around the core set perimeter. Sometimes metallic clips are used to hold the core pieces together. On center leg gapped ferrite cores metallic clips should not result in excessive core loss. With distributed gapped Kool Mμ cores and three leg gapped ferrite cores this is a concern. Leakage flux, which is flowing outside the core structure, concentrates in the metallic clips since the clips have higher permeability than the air-gap. As flux concentrates in the clips excessive losses can occur as shown in figure 13. No significant loss increase was noted with the center leg gapped ferrite core.

CORE LOSS AT 1000 GAUSS
2510 E CORE SET
KOOL Mμ PERMEABILITY OF 26

Figure 13.
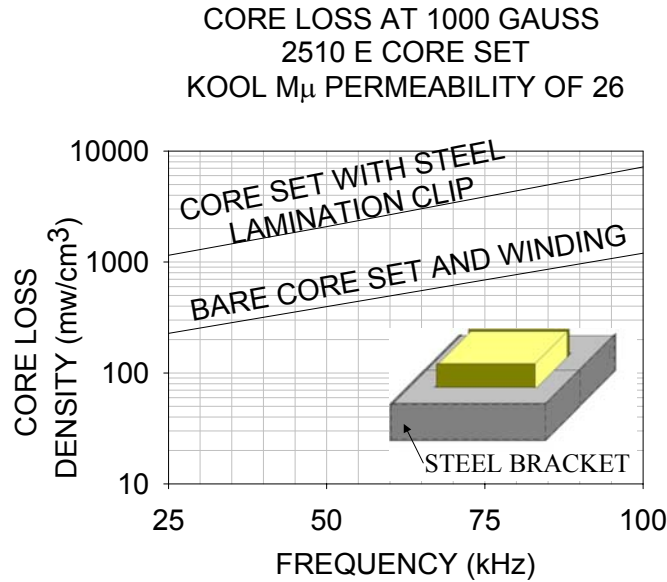
To decrease the external magnetic field and minimize radiated noise a copper screen is often used in transformer construction. This screen is usually a foil with a thickness of about .010 inches and a width covering about one-third of the bobbin length. Figure 14 shows the loss increase due to adding this shield on a 26μ Kool Mμ core. This type of shield would not be effective in containing the external magnetic field of a distributed gapped Kool Mμ core.

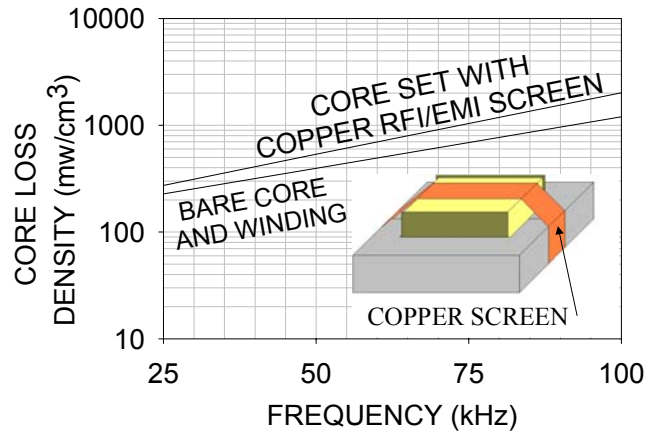CORE LOSS AT 1000 GAUSS
2510 E CORE SET
KOOLMμ PERMEABILITY OF 26

Figure 14.

External Magnetic Field

The external magnetic field of these core structures were investigated by using an F. W. Bell Gauss/Teslameter model number 5080. The cores were driven with a 20kHz ac signal to a level of 2000 Gauss. Since the external field measurement was very sensitive to angular displacement, the meter was set to read the peak field and rotated for the maximum reading. The three maximum field locations are shown in figure 15. Figures 16 and 17 show the strongest field occurred at point A. The field strength was very dependent on both the effective permeability and the type of air-gap.
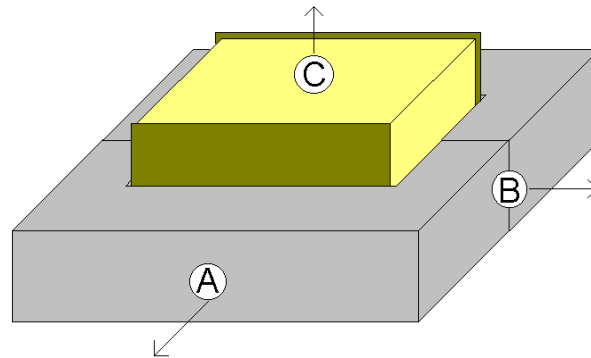

Figure 15.

POSITION "A"
2510 E CORE SET
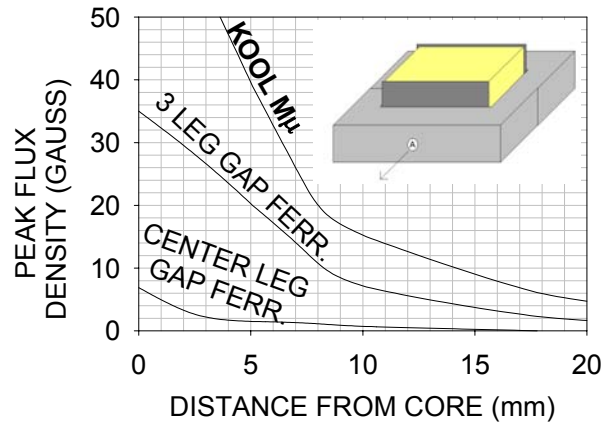EFFECTIVE PERMEABILITY OF 26

Figure 16.

Figure 18 indicates the three leg gapped core has a maximum field at point B. Figure 19, along with the other plots, shows a center leg gapped ferrite has a smaller external filed at all three points when compared to either a Kool Mµ or a three leg gapped ferrite.

A distributed gapped Kool Mµ toroid with a permeability of 60 was also measured under the same conditions. With a high winding fill factor of 40% no external field was measurable. An external field was measured once the winding fill factor was decreased to expose portions of the core.

POSITION "A"
2510 E CORE SET
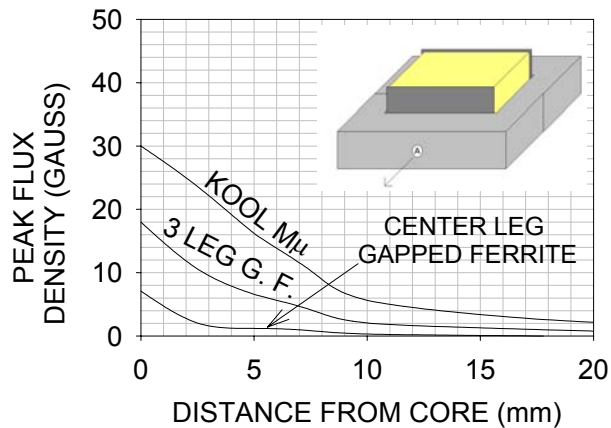EFFECTIVE PERMEABILITY OF 90

Figure 17.

<u>Summary</u>

Three common gapped E core structures were evaluated. Several plots have been presented indicating how the bobbin winding impacts the measured versus calculated inductance. Core loss comparison data was given and accessory pitfalls were shown. The external field strength due to the air-gap was plotted.

POSITION "B"
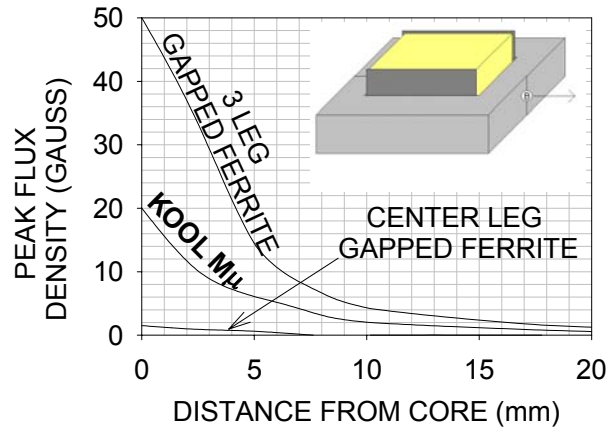2510 E CORE SET
EFFECTIVE PERMEABILITY OF 26

Figure 18.

POSITION "C"
2510 E CORE SET
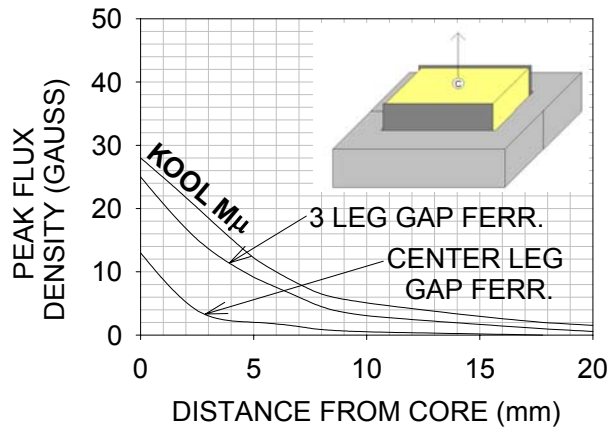EFFECTIVE PERMEABILITY OF 26

Figure 19.